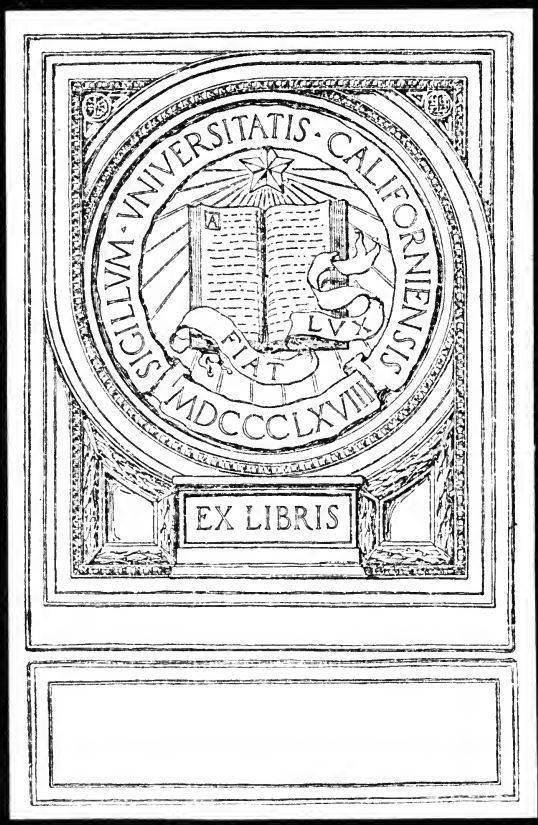
"The Electrician" Series.

STUDIES IN LIGHT PRODUCTION.

BY
R. A. HOUSTOUN, M.A., D.Sc., Ph.D.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STUDIES IN LIGHT PRODUCTION.

BY

R. A. HOUSTOUN, M.A., D.Sc., Ph.D.

Lecturer on Physical Optics and Assistant to the Professor of Natural Philosophy in the University of Glasgow.

WITH 22 ILLUSTRATIONS.

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PREFACE.

THESE studies were written with the purpose of collecting information about the efficiency of our artificial illuminants as energy transformers, both for the sake of rendering the facts readily accessible and also for information as to the lines future progress is likely to take. From this standpoint photometry is not important, and consequently it has not been considered.

The principal scientific journals have been worked through for the past twelve years, but the references to the literature given in the different chapters are not complete, the less important Papers being omitted.

Ten of the twelve chapters have already appeared in THE ELECTRICIAN in a slightly different form, and I am indebted to Mr. W. R. Cooper, Editor of THE ELECTRICIAN, for several valuable suggestions. I am also indebted to Prof. A. Gray, F.R.S., LL.D., for the benefit of his criticism.

R. A. HOUSTOUN.

CONTENTS.

CHAPTER I.

THE ENERGY SPECTRUM.

Light waves carry energy with them. Every source of light is radiating energy, and this energy is being absorbed and converted into heat by the objects on which the rays strike.

When a ray of white light falls upon a prism a spectrum is produced. Part of the energy of the original ray is reflected at the surfaces of the prism, part is absorbed in the prism and the rest is spread over the different colours of the spectrum. Suppose that the spectrum is received on a screen and we fix our attention upon that portion of it bounded by the wave-lengths λ and $\lambda+d\lambda$. The rays, the wave-lengths of which lie between λ and $\lambda+d\lambda$, bring every second a certain amount of energy to the screen; let this amount of energy be denoted by $E_\lambda d\lambda$. E_λ is a function of λ. The total energy arriving per second on the screen is $\int E_\lambda d\lambda$, the integration being carried out over the whole spectrum.

This function E_λ is very important in the theory of the efficiency of light sources, and it is necessary to consider how the variation of E_λ with λ can be determined experimentally. The brightness of the different parts of the spectrum as estimated by the eye is of no use, for the sensitiveness of the eye to different colours is by no means the same. The light energy of the different colours must be turned into heat and the quantity of heat measured. Four different instruments may be used for this purpose—the thermopile, the bolometer, the radiometer and the radiomicrometer. These instruments and the methods of working with them are fully described in Kayser's "Spectroscopie," Vol. I., Chapters V. and VI., and

in Baly's "Spectroscopy," Chapter VIII. There is also an extremely important article in the publications of the Bureau of Standards ("Instruments and Methods of Radiometry," W. W. Coblentz, Bull. Bureau of Standards, 4, p. 391, 1908) in which the relative advantages of the four methods are discussed both from the literature of the subject and as a result of tests made by the author. The radiometer has been used chiefly by E. L. Nichols and his pupils in America. It and the radiomicrometer possess the advantage that they do not require galvanometers and the disadvantage that they cannot be moved during the set of observations. Here I shall mention only a few points about the thermopile and radiomicrometer, of which instruments good types are on the market in this country. (Cambridge Scientific Instrument Co.; Keiser & Schmidt, Berlin-Charlottenburg.)

The Rubens linear thermopile is made of iron and constantan wire of diameter 0·1 mm. to 0·15 mm. It has a resistance of about 4 ohms. Constantan is an alloy consisting of 60 per cent. Cu and 40 per cent. Ni. There are 20 junctions arranged on a length of 2 cm. for receiving the light, and, of course, another 20 unexposed junctions. The junctions are soldered with beads of silver, which are flattened into discs of about 1 mm. diameter, so as to present a large surface to the rays. For mapping energy curves the thermopile is mounted in the telescope of a spectroscope, just behind the focal plane of the latter, and there are shutters in that plane for regulating the width of spectrum that is to be admitted to the thermopile. Wires lead from the thermopile to the galvanometer. When plotting an energy curve—*i.e.*, determining the function E_λ—the source of light is focused on the slit and a screen placed before the latter. The screen is then removed and the galvanometer deflection noted. The operation is then repeated for other points in the spectrum. The galvanometer deflections do not give E_λ directly; the "slit width" correction must first of all be made. Owing to the fact that the dispersion of the prism is not normal, the range of wave-lengths falling on the thermopile at different points in the spectrum—*i.e.*, $d\lambda$—is not always the same. As the deflections are proportional to $E_\lambda d\lambda$, in order to obtain the variation of E_λ we must allow

for the variation of $d\lambda$. To do this we draw the calibration curve of the spectroscope—that is, plot s, the telescope reading in angular measure in terms of λ. If we then determine $\frac{ds}{d\lambda}$ and multiply the deflections by $\frac{ds}{d\lambda}$, the result will be proportional to E_λ.

Another correction must be made before the energy curve is obtained. The absorption of light in the instrument must be corrected for. Glass absorbs all wave-lengths greater than 3μ; but if a glass prism and glass lenses be used, the deflections are influenced by the absorption of the glass from 2μ on. An energy curve cannot be plotted beyond 3μ with a glass prism and lenses, and if the region $2\mu-3\mu$ is to be determined, the absorption of the glass must be allowed for. Quartz transmits much farther into the infra-red and ultra-violet than glass does; but for the infra-red region rock salt and fluorite are the most suitable materials for the prism and lenses. The absorption of the aqueous vapour and carbon dioxide in the atmosphere must be allowed for; at certain wave-lengths it influences the deflections appreciably. It is better to use mirrors in the spectroscope than lenses; all metals reflect infra-red rays well, and the focal length of a mirror being independent of the wave-length, there is no trouble in focusing the thermopile.

In the radiomicrometer we have both thermopile and galvanometer combined. It consists of a single loop of wire with a thermo-junction at one end suspended between the poles of a magnet by a quartz fibre. In comparison with the thermopile it has a very steady zero, but its sensitiveness is distinctly less than that of the latter when connected with a low-resistance Du Bois Rubens galvanometer, which has a resistance of 10 ohms and a sensitiveness of 3×10^{-10} amperes/$\frac{1}{2}$ mm. at 1 metre distance for a period of 5 seconds. As the radiomicrometer cannot be moved, the spectroscope telescope used with it must remain fixed.

Of course, it is only the strongest sources of light, of which the energy curves can be determined directly with a thermopile or similar instrument. The light radiation from the brightest sodium flame produced by a bunsen burner would not produce a readable deflection. If the energy curve of a weak

source is required, the latter must be compared with a strong source by a spectrophotometer in the visible spectrum, and by a photographic method in the ultra-violet, and the energy curve may thus be determined indirectly. There is no means of determining it in the infra-red.

The most satisfactory way of determining the wave-length in the infra-red is to calculate it from the index of refraction of the quartz or fluorite prism, or to place a very thin film of water before the slit and use its absorption bands as reference points. The positions of the latter have been accurately determined. The methods described in the text books—auxiliary gratings and interference bands—are expensive, or much more troublesome.

Suppose, now, that a number proportional to E_λ is plotted as a function of λ from end to end of the spectrum. If we wish to find what proportion of the total energy radiated is light, what we have to do is to erect ordinates at $0{\cdot}410\mu$ and $0{\cdot}760\mu$, the commonly accepted ends of the visible spectrum, and find the ratio of the area included between these ordinates to the area of the whole curve. E. L. Nichols has named this ratio the radiant efficiency of the source. At the same time he has introduced another quantity, the luminous efficiency of the light source. This is defined to be the ratio of the total energy radiated per second as light to the total energy consumed per second by the source.

Let Q = total electrical energy consumed per second, R the total energy radiated per second, and L the total luminous energy radiated per second; then

L/Q=luminous efficiency and

L/R=radiant efficiency, of the lamp.

In the case of an electric glow lamp the total energy consumed per second can be easily found from the current and the difference of potential between the terminals of the lamp. In the case of a gas flame we require to know the total quantity of gas consumed per second and the amount of chemical energy liberated by the combustion of unit mass of gas. The luminous efficiency is always less than the radiant efficiency. If the

energy not radiated were zero—that is, if there were no conduction and convection losses—they would have the same value. Both quantities are extremely useful in the discussion of the performance of a light source.

A glass cell 1 cm. thick filled with water stops all wavelengths greater than $1{\cdot}4\mu$ entirely, and absorbs the infra-red between $1{\cdot}4\mu$ and the visible spectrum considerably, but does not absorb the visible spectrum appreciably. The energy in the ultra-violet of the common light sources is very small indeed, and may be neglected in comparison with the light energy. Hence, in order to separate the light from the dark heat, it used to be the practice to pass the rays through a water filter or through a solution of alum. But a water filter transmits much dark heat as well as light, and if we attempt to determine the radiant efficiency by taking the deflections of a thermopile with and without a water filter before it the value we obtain is much too high. Some experimenters have attempted to correct for the dark heat transmitted by the water by means of solutions of iodine in carbon disulphide, which were supposed to absorb all the light and nothing but the light. The utter untrustworthiness of this correction has, however, been demonstrated by E. L. Nichols and W. W. Coblentz. ("On Methods of Measuring Radiant Efficiencies," Phys. Rev., 17, 1903, p. 267.) Even if we use the correction the values of the radiant efficiency are still too high. Aqueous solutions of ferrous ammonium sulphate have recently been suggested as a means of separating the light from the dark heat. But it has been shown (R. A. Houstoun and J. Logie, Phys. Zs., 11, p. 672) that though they are considerably better in this respect than water filters, yet they are not good enough to afford us a satisfactory method of determining the radiant efficiency. It should be noted that, in spite of the widespread opinion to the contrary, alum solutions do not absorb dark heat any better than water does.

Almost all the accurate determinations of radiant efficiency yet made have been carried out by a method introduced by K. Ångström, which will be described later. I have recently determined ("The Efficiency of Metallic Filament Lamps," Proc. Roy. Soc., Edin., Vol. 30, p. 555, 1910) the radiant effi-

ciency of some metallic filament lamps by a method which, to me at least, seems preferable. The radiation was first measured in the usual way by a thermopile and galvanometer with and without a 1 cm. thick water filter, and the fraction of the total radiation transmitted through the filter determined (F). The light was then focused on the slit of a spectroscope through the same water filter and an energy curve taken. The deflections were plotted against the scale readings and an ordinate set up at $0{\cdot}76\mu$. The area on the side of shorter wave-lengths divided by the whole area then gave the ratio (f) of light transmitted by the filter to the total radiation transmitted. It was then only necessary to find what fraction of the incident light was transmitted by the water cell. This was done with a spectrophotometer for four different points in the spectrum, and the value found, 0·84, was the same for each point. The radiant efficiency was then $F/0{\cdot}84$.

The determination of luminous efficiency is much more difficult. It was the luminous efficiency that was aimed at by the old calorimetric method of measuring the efficiency of a glow lamp. The lamp was placed in a glass calorimeter and then in a similar copper one, and from the rise of temperature in the two cases, with various corrections, the ratio of the energy radiated as light to the whole energy supplied could be calculated. The heat lost by convection and conduction went to raise the temperature in both cases. But the method is in principle bad; the whole energy and the dark heat are measured and the light is obtained as the difference of two much larger quantities, both subject to considerable error of observation. Also, as has been already mentioned, water does not absorb all the dark heat, and hence some escapes from the glass calorimeter. If we wish to determine the luminous efficiency we must first of all determine the radiant efficiency; we must then find the total rate at which energy is being consumed by the source, and we must finally determine the total energy radiated per second. The neatest way of finding the energy radiated per second in any one direction is by some such instrument as Ångström's pyrheliometer. To find the total energy radiated per second it is necessary to find the energy radiated in different directions and to integrate over the sphere.

So far we have considered light solely from the objective standpoint. It is now necessary to consider it in relation to the eye. The same quantity of energy in different parts of the spectrum does not produce the same intensity of sensation in the eye. The well-known curve shown in Fig. 1, taken by Sir Wm. Abney, illustrates this. The brightness of the different colours of the spectrum of the crater of the arc was compared in turn with the brightness of a white light, which could be varied by a rotating sector. The ordinates of the curve are obtained in this way, and are proportional to the brightness or luminosity of the part of the spectrum in question as seen by a normal eye. If we took an energy curve of the arc crater with the same prism and lenses, plotted it on the same diagram and divided the ordinates of the energy curve by the ordinates of the luminosity curve, the quotient would be proportional to the quantity of energy necessary to produce the same luminosity at different points in the spectrum. It varies widely throughout the spectrum, having a minimum at 510 $\mu\mu$ for low intensities and increasing rapidly on both sides of this minimum. At 410 $\mu\mu$ it has then a value roughly 50 times the minimum value, and at 610 $\mu\mu$ one roughly 40 times the minimum value. According to P. G. Nutting ("The Luminous Equivalent of Radiation," Bull. Bureau of Standards, 5, p. 273, 1908). who refers to the reciprocal of this quotient as the visibility of the colour, the quotient for low intensities has the form $e^{\kappa(\lambda-\lambda_m)^2}$ for the normal eye, λ_m being the wave-length of the minimum measured in 10^{-5} cm., and κ being equal to 4·5.

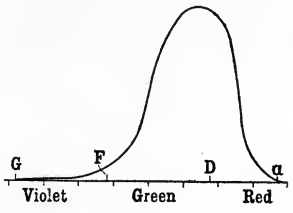

FIG. 1.

For higher intensities the maximum of visibility moves towards the yellow, and the visibility in the neighbourhood of the maximum does not vary so much with colour. At low intensities vision seems to be performed by the retinal rods alone, and at higher intensities mainly by the cones. The transition from rod to cone vision is very gradual; they are

about equally in play at ordinary working intensities. It is the transition from rod to cone vision that displaces the maximum of visibility with increase of intensity.

As the brightness of the light produced depends not only on the energy of the radiation, but also on its colour, luminous efficiency, as we have defined it, has no direct connection with efficiency as ordinarily understood in connection with artificial illuminants. One source which radiates more energy between 410 $\mu\mu$ and 760 $\mu\mu$ than another may have that radiation distributed so disadvantageously over the spectrum that it gives less light than the other. C. E. Guillaume has, therefore, proposed to specify the efficiency by multiplying E_λ for every wave-length by the "visibility" for that wave-length, taking the maximum visibility in the spectrum as unity, and by dividing the quantity thus formed by the total power supplied.*

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* This proposal has been taken up by C. V. Drysdale ("Illuminating Engineer," Vol. I., 1908) and H. E. Ives (Trans. of Amer. Illuminating Engineering Society, February, 1910). Drysdale proposes the name "reduced luminous efficiency" for the quantity obtained by multiplying the energy radiated per wave-length per second by the visibility for that wave-length, integrating throughout the spectrum and dividing by the energy consumed per second by the source, the maximum visibility in the spectrum being taken as unity. Reduced luminous efficiency is, then, proportional to candles per watt; but what is more, it expresses the fraction of the applied energy, which would be sufficient to give the same quantity of light had all the energy been radiated as yellow-green light. If we multiply the energy radiated per wave-length per second by the visibility for that wave-length, integrate throughout the spectrum, and divide by the total energy radiated, we obtain the "reduced radiant efficiency." Much the best way of determining the latter will be to measure the fraction of the radiation transmitted through the colour filter which I describe in Chap. XI.

Ives gives the following values for reduced radiant efficiency :—

Hefner lamp	0·0018
"4 watt" carbon lamp	0·0043
Black body at 6000°abs.	0·156

It should be noted that Ives has also introduced another term, "daylight efficiency" (Bull. Bureau of Standards 6, p. 231, 1910), to denote the ratio of the intensity of white light obtainable from any source by passing it through a suitably coloured screen to the intensity of the original source.

It may be urged against this proposal that the visibility of different colours is not very well known yet, and that in watts per candle or in candles per watt we have already a term that conveys Guillaume's meaning. Also the relative visibility of the different colours varies with their intensity; and the ordinary method of testing lamps on the photometric bench is certainly a much shorter and more accurate method for getting their watts per candle than the one suggested in Guillaume's definition. It seems to me, therefore, better to retain the old way of specifying luminous efficiency. It has, in addition, the merit of simplicity.

Various observers at different times have attempted to determine what has been called the mechanical equivalent of light—namely, how much energy it is necessary for a source to radiate per second in order to produce 1 c.p. of light. From the foregoing it is obvious that the mechanical equivalent of light must vary with the nature of the source. As a result of a recent determination, C. V. Drysdale ("On Luminous Efficiency and the Mechanical Equivalent of Light," Proc. Roy. Soc., A, 80, 1907-08, p. 19), using glow lamps, obtained 16·7 candles per watt for yellow-green light.

The visibility is greatest for green light. This, consequently, is the cheapest kind of light; but, being monochromatic, it is of no use for the purpose of discriminating colour. The ideal illuminant must make all colours appear the same at night as by day. It might be possible to make a creditable white light by combining two monochromatic sources, but for making all colours appear the same by night as by day the illuminant must have all the colours of the spectrum in the same proportion as average sunlight. Consequently, we arrive at the specification of the energy curve of the perfect artificial illuminant after which technology is striving. *Throughout the visible spectrum it will have an energy curve like that of average sunlight; the energy curve will cease at the limits of the visible spectrum.*

In an interesting article (Trans. of Amer. Illuminating Engineering Society, April, 1910) H. E. Ives has calculated the energy curve of sunlight under different conditions, using all the available data, and finds that its average value has the

same shape as the curve for a black body at 5000°abs. He then makes the interesting and important statement that the maximum of this curve coincides with the maximum of sensibility of the human eye. This is not a coincidence, but the result of adaptation through long ages. We thus have a criterion for average daylight more exact than could be obtained by any series of daylight measurements, no matter how large.

CHAPTER II.

THE BLACK BODY.

According to the modern view, light may be produced in two ways, by temperature radiation and by luminescence. If the source is emitting light merely as a result of being heated, and if it is not suffering any chemical change in the process, we have a case of temperature radiation. The electric glow lamp, the Nernst filament and the incandescent mantle belong to this class. Here the electrons which emit the light waves are caused to vibrate as a result of the motion of the molecule as a whole. If, on the other hand, light is produced, not as a result of heat, but as a result of electric energy being conveyed to the source, or as a result of chemical energy being liberated, we have luminescence. The aurora borealis, the vacuum tube, the light given off by phosphorus in the dark, are all cases of luminescence. In these cases the source is cold, and no kinetic energy is given to the atom or molecule as a whole.

Luminescence has not been studied much from the point of view of the energy curve, chiefly on account of experimental difficulties. Temperature radiation has been studied very fully and accounts of the principal facts have been given by Kayser, Day and Van Orstrand, and Waidner and Burgess. (Kayser's "Spectroscopie," Vol. II., Chapters I. and II. Arthur L. Day and C. E. Van Orstrand, "The Black Body and the Measurement of Extreme Temperatures," Astrophys. J., 19, p. 1, 1904. C. W. Waidner and G. K. Burgess, "Optical Pyrometry," Bull. Bureau of Standards, 1, p. 189, 1905.)

In 1859 Kirchhoff published the law that the ratio of the radiating power to the absorbing power of all bodies is the same

and a function of the wave-length and the temperature. By the radiating power of a body is meant the quantity of heat radiated from unit area of its surface in unit time; by the absorbing power is meant that fraction of the energy incident on the surface which is absorbed by the body.

The law may be proved for one particular case as follows: Let CDFB, GJHK (Fig. 2) be pieces of two bodies. They have the form of slabs extending to infinity on all sides. Let the faces CB, JK, which are turned away from one another, be impervious to heat. Let E_1, A_1 denote the radiating power and absorbing power of the body on the left, and E_2, A_2 the radiating power and absorbing power of the body on the right.

Suppose that there is equilibrium of temperature between the two bodies. Then each receives as much heat as it radiates. From the shape of the bodies it is evident that the radiation from each must be normal to their surfaces. It is sufficient, therefore, to consider the unit area of the one surface and the unit area of the other surface opposite it. Consider the energy E_1 originally emitted from 1. A_2E_1 is absorbed by 2, $(1-A_2)E_1$ reflected. Of the reflected energy $(1-A_2)A_1E_1$ is absorbed by 1, $(1-A_2)(1-A_1)E_1$ reflected. Of this $(1-A_2)(1-A_1)A_2E_1$ is absorbed by 2, and so on. It is easy to see that the quantity absorbed by 1 is

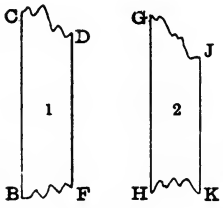


FIG. 2.

$$(1-A_2)A_1E_1+(1-A_2)^2(1-A_1)A_1E_1 + (1-A_2)^3(1-A_1)^2A_1E_1 \ldots$$

$$=(1-A_2)A_1E_1\{1+(1-A_1)(1-A_2)+(1-A_1)^2(1-A_2)^2 \ldots\}$$

$$=\frac{(1-A_2)A_1E_1}{1-(1-A_1)(1-A_2)};$$

and the quantity absorbed by 2 is

$$A_2E_1+(1-A_1)(1-A_2)A_2E_1+(1-A_1)^2(1-A_2)^2A_2E_1 \ldots$$

$$=\frac{A_2E_1}{1-(1-A_1)(1-A_2)}.$$

If we interchange the suffixes we obtain the quantity of the energy E_2 that is absorbed by 1. It is

$$= \frac{A_1 E_2}{1-(1-A_1)(1-A_2)}.$$

The total quantity of energy absorbed by 1 is

$$\frac{(1-A_2)A_1E_1}{1-(1-A_1)(1-A_2)} + \frac{A_1E_2}{1-(1-A_1)(1-A_2)}$$

$$= \frac{(1-A_2)A_1E_1+A_1E_2}{A_1+A_2-A_1A_2}.$$

This must equal E_1. Therefore

$$(1-A_2)A_1E_1+A_1E_2=(A_1+A_2-A_1A_2)E_1.$$

Hence $$A_1E_2=A_2E_1,$$

or $$E_1/A_1=E_2/A_2,$$

which proves the proposition.

The only form of energy considered by the proof is heat. Hence the above quantitative relation holds only for temperature radiation. The body must radiate solely on account of its high temperature, and not in virtue of electromagnetic energy received or of chemical energy liberated. Under this limitation the law is universally accepted as true. Numerous facts point to its truth, and Paschen has verified it quantitatively. How far it holds for luminescence is not known.

A very important result follows at once from the law. A body cannot emit those rays which it totally reflects, or for which it is perfectly transparent. If the surface of the body is a perfect mirror, all the incident light is reflected, none is absorbed and A is equal to zero; again, if the body is transparent, the intensity of the light is not altered by passing through it, and A is again equal to zero. If A is zero, E must also be zero.

In the rigorous proof of his law Kirchhoff introduced the idea of a perfectly black body. A perfectly black body is one for which $A=1$; that is, one which absorbs all the rays which fall upon it. Hence, for any given wave-length and temperature,

no body can radiate more than a black body. None of the surfaces which we are accustomed to regard as black is black in this sense. They all reflect some of the incident light. Black cloth, for example, reflects 1·2 per cent. of the light that falls on it, and black velvet 0·4 per cent. Let the radiating power of the black body be denoted by S. Then $E/A=S$; S gives the ratio of the radiating power to the absorbing power for any body, and is a function of the wave-length and the temperature. Kirchhoff pointed out the importance of determining the function S, and stated that it would undoubtedly be of a simple form, as it was independent of the properties of any particular body. S is sometimes called Kirchhoff's function.

It would be extremely difficult to measure E and A for one particular body for different wave-lengths and thus determine S, for, of course, A would have to be measured at the same temperature as E—that is, while the body is radiating. Paschen commenced a series of researches in 1892 with the purpose of determining S, the method being to measure E for a series of bodies which were more or less black. Then, if these bodies were arranged in order of their "blackness," it would be possible by a species of extrapolation to arrive at the behaviour of the ideal black body. Paschen used a piece of platinum foil folded double, in the fold of which a thermo-element was placed for the purpose of determining its temperature. The foil was heated by a current from a secondary battery, and was coated with the substances the radiation from which was to be examined. The radiation was measured with a bolometer; the spectral apparatus had concave mirrors instead of lenses, and the prism was of fluorite. The substances used were carbon filaments, platinum foil, platinum foil covered with iron oxide, copper oxide and soot. They all behaved pretty much the same with the exception of platinum, which radiated considerably less.

Meanwhile, attempts were being made from the theoretical side to find S as a function of λ and of T, the absolute temperature. In 1896 Wien gave the following expression:—

$$S=\frac{c_1}{\lambda^5}e^{-\frac{c_2}{\lambda T}},$$

which was afterwards derived by Planck in another manner. The proofs are not simple and are not quite beyond question.

The next important step was the experimental realisation of the perfectly black body by Lummer and Pringsheim. A perfectly black body is one that absorbs all the rays that fall on it and reflects none. Consider the accompanying diagram (Fig. 3). It represents a section of a hollow sphere which has a small opening at AB. R is a ray which enters the opening and is reflected in succession at C, D, E and F. The inside surface of the sphere is blackened. Only a small portion of the energy is reflected each time, the greater part being absorbed. The hole AB is of such a size that the chances of the ray finding its way out again are very small. Light falling on AB is practically all absorbed. Consequently, if the sphere be maintained at a uniform temperature, sufficiently high to make its inner surface radiate out heat appreciably, the radiation from AB will be the radiation of the black body for that temperature, or the black radiation for that temperature, as it is called Also, if any body be heated inside the sphere to the temperature of the latter, the radiation issuing from its surface through the opening will be black radiation.

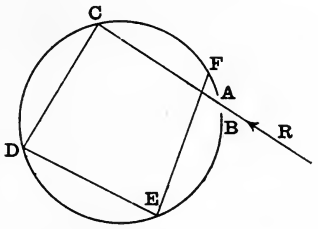


FIG. 3.

For low temperatures double-walled vessels were used, the space between the walls being filled with steam, ice, carbon dioxide, snow or liquid air, so as to keep the interior at a uniform temperature. The radiation escaped by means of a tube. For high temperatures an electrically-heated body of porcelain was used.

With this apparatus Lummer and Pringsheim first proved Stefan's law for the black body, showing that the radiation was proportional to the fourth power of the absolute temperature. Then, in 1899, they published energy curves taken with the same radiators. These energy curves are reproduced in the following diagram (Fig. 4).

Thus Kirchhoff's function S was determined as a function

of λ for several different values of T. Lummer and Pringsheim's results did not agree so well with Wien's formula as Paschen's results did, and further investigation showed that Lummer and Pringsheim's results were the more accurate. As a result of their work Planck proposed the following formula :—

$$S=\frac{c_1}{\lambda^5}\frac{1}{e^{\frac{c_2}{\lambda T}}-1},$$

which he sought to justify on theoretical grounds. It represents the experimental results satisfactorily within the error of observation.

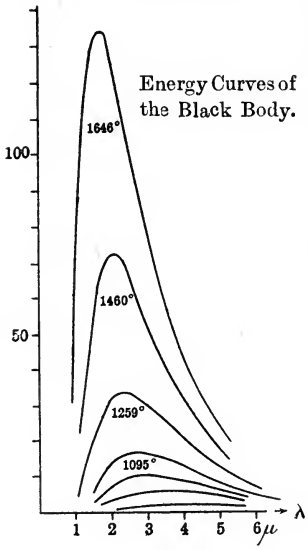


FIG. 4.

On comparing Planck's formula with Wien's we notice that it is only when $e^{\frac{c_2}{\lambda T}}$ is not large in comparison with 1 that they differ appreciably — that is, only for high temperatures and large values of λ. Wien's formula may thus be regarded as an approximate form of Planck's, and has the advantage of simplicity. From it a number of important results about black body radiation can be deduced.

We have $S=c_1\lambda^{-5}e^{-\frac{c_2}{\lambda T}}$. To find for what values of λ S is a maximum take the logarithm of S, differentiate it with respect to λ, and equate to zero.

$$\text{Log } S=\log c_1-5\log\lambda-\frac{c_2}{\lambda T},$$

$$-\frac{5}{\lambda}+\frac{c_2}{\lambda^2 T}=0.$$

Hence $$\lambda T=\frac{c_2}{5}.$$

Denote the value of λ corresponding to the maximum value of

S by λ_m. When T is measured in degrees abs. and λ_m in 10^{-4}cm. $c_2=14{,}500$. Therefore

$$\lambda_m T = 2{,}900.$$

As the temperature increases the maximum moves towards the visible spectrum. By substituting λ_m in the expression for S, we find that the maximum value of S increases as the fifth power of the absolute temperature. S always increases with temperature for every value of λ, no matter on which side of the maximum it is.

To find the total radiation, integrate $\lambda^{-5}e^{\frac{c_2}{\lambda T}}$ from $\lambda=0$ to $\lambda=\infty$. The integration follows easily if λT is put $=1/\theta$, and θ is regarded as the variable. The result is $6T^4/c_2{}^4$. This is Stefan's law. It holds only for the black body; Stefan thought that it held for all bodies.

The radiant efficiency may be found by integrating S between the limits λ_1 and λ_2 and substituting the values for the ends of the visible spectrum; but there is a more convenient graphical method. When $1/\theta$ is substituted for λT, the integral takes the form $c_1 T^4 \int \theta^3 e^{-c_2\theta} d\theta$. The values of θ corresponding to the ends of the spectrum depend on the value of T. If the curve $\theta^3 e^{-c_2\theta}$ be plotted, if ordinates be setupat values of θ corresponding to the ends of the visible spectrum for different temperatures, and if the areas between the ordinates be determined graphically and divided by the area of the whole curve, then we obtain the values of the radiant efficiency for these temperatures. The following results have been obtained in this way :—

Abs. temp.	Radiant efficiency.
1,000	0·0 per cent.
1,500	0·0 ,,
2,000	1·7 ,,
3,000	14·6 ,,
4,000	31·8 ,,
6,000	49·7 ,,
8,000	47·7 ,,
12,000	18·6 ,,

Thus 7,000 deg. abs. gives the most favourable result. Above this the intensity maximum moves into the ultra-violet.

The temperature radiation of bodies that are not black follows more complicated laws. The energy curves vary all the way from shapes not differing widely from that for the black body to curves with two or three sharp maxima. The wave-length of maximum intensity, however, always decreases as the temperature increases, and many substances which radiate selectively at low temperatures become similar to the black body at high temperatures. Of course, no body can radiate more than a black body for any wave-length and temperature.

The metals form an interesting class, and an attempt has been made to represent their energy curves by formulæ of the same form as Wien's, but with a different power of λ in place of the λ^{-5}. ("Radiation Constants of Metals," W. W. Coblentz. Bull. Bureau of Standards, 5, p. 339, 1909.) At ordinary temperatures they all reflect much better in the infra-red than in the visible spectrum (*Cf.* for example the table on p. 102). Hence their absorbing power, and consequently their radiating power, is less in the infra-red. This selective reflection seems to persist at high temperatures, and the energy curves resemble the black body somewhat, but with the ordinates on the infra-red side of the maximum diminished, and consequently the radiant efficiency increased. Lummer and Pringsheim's curves, representing the radiation from glowing platinum at different temperatures, are given by the diagram on the next page (Fig. 5). The total radiation from platinum varies as the fifth power of the absolute temperature.

The theory of the black body has been applied in three different ways to the measurement of temperature. Temperature may be read by the hydrogen thermometer up to 600°C., and thence by the nitrogen thermometer to 1,150°C. Beyond this it is customary to use thermo-couples which have been calibrated as far as the gas thermometers go and to extrapolate for values beyond. Thermo-couples are, however, unsuitable for some purposes, and in any case they cannot be used beyond the melting point of platinum. This is where optical pyrometry finds its use.

The first optical method consists in finding the position of λ_m and applying the equation $\lambda_m T = 2{,}900$. The second consists in measuring the total radiation by some instrument such

as Féry's thermo-electric telescope and using Stefan's law, or as it is now more often called the Stefan-Boltzmann law. In this instrument an image of the source is formed on a thermo-couple by a concave mirror, and the instrument is calibrated by pointing it at two sources of known temperature. The third method consists in measuring the brightness of the source for one wave-length in the visible spectrum and calibrating the photometer by means of two sources of known temperature.

These methods give relative measurements satisfactorily and enable one to reproduce any temperature with accuracy, which is all that is required for industrial purposes ; but they must be used with considerable care if absolute measurements are required. There are many people in possession of optical pyrometers who are, unfortunately, unaware of the limitations of their instrument, and have too profound a faith in its empirical formula.

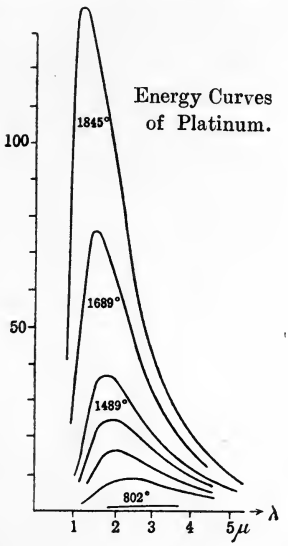


FIG. 5.

All three methods hold in the first instance only for the black body. The first method holds also for a "grey" body—that is, one that reflects all colours equally well. In the case of a grey body the ordinates of the energy curve are supposed to be diminished in the same ratio all over and the position of the maximum is unaltered. The first method is, however, not so accurate as the other two, for the position of the maximum cannot be easily determined. The last two methods if applied indiscriminately will not give the true temperature of a body, but its "black" temperature—that is, the temperature of a black body which would have the same total radiation, or which would have the same brightness for the wave-length in question.

To get the true temperature we may proceed in two ways. On the first method, which is due to Lummer and Pringsheim,

the scale of the instrument is calibrated by using glowing platinum as well as the black body. We thus have two determinations of the temperature, the second value being that which the body would have if it had the same properties as platinum. As platinum differs widely from the black body as a radiator, there is a presumption that the true temperature of the body will lie between the limits thus obtained. On the second method, the body is placed inside a sphere, the inner surface of which is a good reflector, and the radiation through a hole in the surface examined. The radiation from the body is thus increased until its black temperature equals its true temperature.

Optical pyrometry has been applied to the determination of the temperature of the sun, and values somewhat below 6,000°C. have been obtained and have found their way into the text-books. In a recent paper (Ann. d. Phys. (4), 25, pp. 905-920, 1908), Dr. A. Goldhammer, however, finds its temperature to be 10,000°C. If the sun is a black radiator at 6,000°C., according to the table given above, this is not far from its most economic temperature. As has been mentioned already, it is not the sun that has adapted its temperature to our eyes, but our eyes which have suited themselves to the sun through long ages of evolution.

CHAPTER III.

FLAMES.

Flames are the simplest and historically the first means of producing light. When or how prehistoric man first learned the use of fire we know not. The ancient Greeks ascribed a supernatural origin to it in the myth of Prometheus, and other lands have other legends ; but it was probably obtained at first accidentally by a spark from a flint. Be that as it may, the mastery and use of fire is one of the signs that distinguish man from the brutes, and marks the first stage in the development of the artificial light of to-day.

As different stages in this development we have the primitive pine torch, the oil lamp of the ancients, which attained a great development in ancient Rome, the rush light of the Middle Ages, the different kinds of candle, from the tallow dip to the modern paraffin candle, the burning whale, seal or bear fat of the Esquimaux, the Argand lamp, ordinary coal gas and acetylene gas. In all these cases light is produced in substantially the same way—by the flame formed when hydro-carbons are burned in air. The spectra produced have in every case essentially the same character ; upon the continuous spectrum of the incandescent carbon particles is superimposed the discontinuous spectra of the gaseous products of combustion, principally water vapour and carbon dioxide.

To gain an insight into the mechanism of the flame we shall therefore study as a typical case the candle, which has been made the subject of a course of six lectures by Faraday. (" The Natural History of a Candle." New Edition. London, 1894, Chatto & Windus.) When an ordinary paraffin candle

is burning, a cup is formed at the foot of the wick. The flame melts the paraffin at the foot of the wick, while the air moving upwards by the force of the current, which the heat of the candle produces, keeps the sides cool and prevents the edge from melting. The fluid in the cup is sucked up the wick by capillary attraction. After travelling up the wick the fluid vaporises and is burned as a vapour in the flame, the heat of combustion vaporising more fluid and thus maintaining the flame. The flame travels down the wick until it is put out by the fluid in the cup. The top of the wick bends over and is consumed in the edge of the flame. In a candle, gas is manufactured for combustion just as on a large scale in the gas works of our cities.

A candle flame on examination is seen to consist of four regions. First of all there is a transparent part round the wick. It may be shown by withdrawing some through a glass tube that the transparent part consists of vapour before combustion. Below this, on the edge of the flame, there is a blue part, due to the formation of carbon monoxide. This blue part gives the Swan spectrum, and it is not known whether the latter is due to carbon or carbon monoxide. There is recent work favouring both views. Above the transparent part is the bright opaque region, which gives far the greater part of the light of the flame, and finally the flame is surrounded by a faintly luminous mantle, which in the case of the candle is somewhat difficult to see. The chemical actions occurring in the different regions of the flame are complicated and not thoroughly understood; but the bright part is due to incandescent carbon particles from the vapour after its decomposition, before they combine with the oxygen of the atmosphere to form carbon dioxide. These bright particles are carried upwards by the air current. Smoke is due to the carbon particles not having sufficient oxygen to combine with. In the Bunsen flame, on the other hand, the oxygen combines with the carbon before the latter has time to radiate as a solid.

Energy curves of flames have been taken by G. W. Stewart ("The Spectral Energy Curve of the Acetylene Flame," Phys. Rev., 16, 1903, p. 123), K. Ångström ("Energy in

the Visible Spectrum of the Hefner Standards," Phys. Rev., 17, 1903, p. 302) and R. Ladenburg (" Uber die Temperatur der glühenden Kohlenstoffteilchen leuchtender Flammen," Phys. Zs., 7, 1906, p. 697). Stewart gives a very carefully taken energy curve of a cylindrical acetylene flame. The light was resolved by a mirror spectroscope with a fluorite prism, and the energy measured by a radiometer. The curve is reproduced below (Fig. 6).

The elevations at 1·46μ and 1·90μ are emission bands of the water vapour, and the maxima at 2·6μ and 4·4μ emission bands of the carbon dioxide in the flame, the remainder of the area being due to the glowing carbon. Stewart also gives the energy curve of an ordinary gas flame. (" The Temperatures and

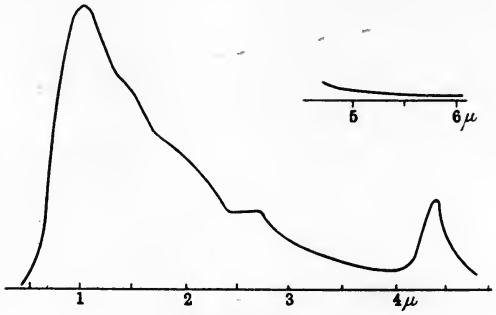


Fig. 6.

Spectral Energy Curves of Luminous Flames," Phys. Rev., 15, 1902, p. 306.) It has the maximum at 1·13μ. Ångström gives a prismatic energy curve for the amyl acetate flame of the Hefner lamp. It shows the two emission bands of carbon dioxide very clearly, but there are depressions at the positions of the two water bands, showing that more energy is absorbed by the water vapour in the atmosphere than is emitted by the water vapour in the flame. Ångström uses a rock-salt prism and bolometer. Ladenburg gives both the energy curves for the acetylene flame and the Hefner lamp, taken with a mirror spectroscope, quartz prism and thermopile, but not so far into the infra-red. Both his curves show the absorption bands of

water, and in the Hefner lamp curve the carbon dioxide band nearer the shorter wave-lengths—the only carbon dioxide band shown—appears as an absorption band. The maximum of his acetylene flame is at 1·21, and its shape does not agree well with Stewart's curve.

The temperatures of the acetylene, gas and candle flames have been measured by E. L. Nichols ("On the Temperature of the Acetylene Flame," Phys. Rev., 10, 1900, p. 234) with a platinum platinum-rhodium thermo-element. The introduction of a thermo-element into the flame lowers the temperature of the flame. Four different thermo-junctions were therefore used, made of wires of different diameter. The thinner the wire the higher was the temperature recorded; hence, by plotting the temperature as a function of the diameter of the wire and continuing the curve, he found what temperature would be recorded by an infinitely thin wire. The determination was also complicated by soot forming on the junction and lowering its temperature, and, in the case of acetylene, by the junction melting. The thermo-element was gradually pushed into the flame and the readings plotted as a function of the distance from its centre until the junction melted or soot began to form. Then the portion of the curve found was simply produced to the centre of the flame. In this way the centre of the luminous region of the acetylene flame was estimated to be at 1,900°C., while the sheath surrounding the luminous region may be 20°C. higher. The luminous region of the gas flame was found to be not more than 1,780°C., and the hottest portion of the candle flame to be 1,670°C. From the diagram given the average value for the luminous region of the latter is probably 100°C. lower. In standardising his thermo-element Nichols took the melting point of platinum as 1,775°C.

Assuming that the carbon in flames radiates more selectively than a black body and less selectively than platinum, and using the formulæ established by Lummer and Pringsheim for the maximum of the energy curve in these cases—namely,

$$\lambda_m T_{max.} = 2{,}940,$$

$$\lambda_m T_{min.} = 2{,}630,$$

we obtain the following results :—

	λ_m	$T_{max.}$	$T_{min.}$
Candle	1·5	1,687°C.	1,477°C.
Argand lamp.....	1·55	1,627°C.	1,427°C.
Acetylene flame ...	1·05	2,527°C.	2,232°C.

The formulæ give the temperatures in degrees abs., but in the table they are expressed in degrees cent. $T_{max.}$ is the temperature which the flame would have if we assume that it radiates as a black body, $T_{min.}$ if we assume that it radiates as platinum.

The value thus obtained for the temperature of the acetylene flame is very much higher than Nichols' value. Stewart states that he considers it much too high. Kurlbaum suggests the cause of the difference (Phys. Zs., 3, 1902, p. 187). While a luminous flame of very great thickness may be expected to radiate as a black body, yet we may expect a candle flame to radiate as a very thin film of soot at that temperature. Now lamp black is more transparent to long waves than short waves—*i.e.*, the absorption and radiation increase with decrease of wave-length. Hence on applying the formula $\lambda_m T = \text{const.}$ the temperatures obtained will be too high, for the maximum will be much farther towards the short wave-lengths than in the case of a black body at the same temperature. Thus, according to Kurlbaum, the radiation of glowing carbon is usually more selective than that of bright platinum.

This has been proved by Ladenburg (loc. cit.). As has been already stated, he took an energy curve of the acetylene flame and of the Hefner lamp. He then caused the light from a Nernst glower to pass through these flames and plotted the percentage absorbed as a function of the wave-length, thus determining the absorption as well as the emission of the flame. The absorption of both flames increases as the wave-length decreases. If now we divide the emission by the absorption we obtain the emission of the theoretical black body at the same temperature. As a final result, Ladenburg obtains 1,838°C. for the acetylene flame and 1,431°C. for the Hefner flame. He states that Nichols' value of the melting point of platinum is 55°C. too high. The latter's value for the centre

of the flame should thus be 1,845°C., which is in very good agreement with his own.

The platinum melting point is now supposed to be about 1,755°C., 20° lower than Nichols' value.

Stewart (loc. cit.) finds the radiant efficiency of the acetylene flame to be 0·039. The result was obtained by dividing the area of the energy curve to the left of 0·76μ by its whole area. K. Ångström had previously found it to be 0·055. K. Ångström has also made a very careful determination of the radiant efficiency of the Hefner lamp by an original method. He first took the energy curve, and found that, in the visible spectrum and in the infra-red as far as 1·5μ, it agreed with the curve of a certain glow lamp for one particular current. By means of a prism and screen the light from the glow lamp was separated from its heat rays. After the heat rays were separated out the light rays were allowed to come together again and fall on one face of a wedge photometer on the other face of which the light from a Hefner lamp fell, and the distance of the latter adjusted until balance was obtained. The photometer was then removed and a bolometer placed in exactly the same position. The intensities of the two beams were then measured in succession by the bolometer; their ratio gave the radiant efficiency. The value found was 0·0096.

For an oil lamp with glass funnel W. Wedding finds 0·01 by the water-filter method.

So much for the radiant efficiency—the ratio of light emitted to total radiation. But the question arises of the luminous efficiency—the ratio of the light emitted to the total energy consumed. In order to determine the latter we require the total radiation in absolute measure, the rate at which the substance is being burned and the calorific value of its unit mass. For the case of the Hefner lamp the ratio of the whole energy radiated to the energy consumed has been calculated by O. Tumlirz, and we take the following details from his article ("Die Wärmestrahlung der Wasserstoffflamme," Wien. Ber., 113 (Abt. II.a), 1904, pp. 501-509). The energy received by a surface element at a distance of 1 metre from a Hefner lamp is $1{\cdot}62\ 10^{-5}$ gm. cals. per square centimetre per second, the surface element being normal to the straight line joining

it to the flame and the latter line being horizontal. K. Ångström (loc. cit.), it may be noted, found $2{\cdot}15\ 10^{-5}$ gm. cals. per square centimetre per second for the same quantity by means of his pyrheliometer. Hence in a second the flame radiates $4\pi \times 10^4 \times 1{\cdot}62\ 10^{-5} = 2{\cdot}04$ gm. cals. The quantity of amyl acetate burned in a second is 0·002678 gms. According to Favre and Silbermann the heat of combustion of 1 gm. of amyl acetate is 7,971·2 gm. cals.; hence the heat given out by the Hefner lamp in one second is $7971{\cdot}2 \times 0{\cdot}002678 = 21{\cdot}35$ gm. cals. We arrive, therefore, at the result that the ratio of energy radiated to energy consumed is 2·04/21·35, or 0·0956. The greater part is lost by convection. If we assume Ångström's value for the radiant efficiency, namely, 0·0096, the luminous efficiency becomes $0{\cdot}0096 \times 0{\cdot}0956 = 0{\cdot}00092$; that is, the efficiency of the Hefner lamp as an energy transformer is less than one-tenth per cent. There is no reason to believe that our ordinary illuminating gas is any better.

In the same article, Tumlirz describes a determination of the ratio of the total energy radiated to the energy consumed by a hydrogen flame. The value found was 0·0615.

CHAPTER IV.

THE WELSBACH MANTLE.

The incandescent gas light was invented by Karl Auer, Freiherr von Welsbach, in 1885. He had been a pupil of Bunsen at Heidelberg, and before the invention of the light had made a thorough study of the rare earths. The principle of the light is that a mantle of organic material is impregnated with a mixture of thorium oxide and cerium oxide in the proportion of about one part of the latter to 99 parts of the former; the organic material is then burned off, the oxides remain and are heated in the colourless Bunsen flame until they radiate light. It is known that Auer von Welsbach did not come upon the discovery suddenly, but that he experimented systematically with different earths in order to get a mixture which, when heated in the Bunsen flame, would give a stronger light than its components.

On its appearance the Welsbach mantle created quite a stir in the scientific world, and the cause of its brilliancy was very much discussed. It follows quite simply from the ordinary laws of temperature radiation, but at first this was not definitely known, and other explanations such as luminescence and catalysis were forthcoming.

It was assumed that the Welsbach mantle radiated more than a black body at the same temperature, and that, consequently, its radiation could not be pure temperature radiation. Nichols and Snow (Phil. Mag., 33, 1892, p. 19) had found that when platinum foil was covered with zinc oxide and heated electrically to incandescence its light was very strong at first, but that during the first 10 minutes it diminished considerably, although the temperature was kept constant. Afterwards the intensity became constant. Hence they assumed that the light

was composed of two parts: one part which remained constant, consisting of temperature radiation, and another part which diminished rapidly, consisting of thermo-luminescence. The source of the energy of this latter part was to be found in a physical or chemical change in the incandescent body, such as one from the amorphous to the crystalline condition. If the Welsbach mantle were thermo-luminescent, we would thus have not only an explanation of its high luminosity but also of the diminution of its intensity with time.

But an experiment described by H. Bunte ("Uber die neure Entwickelung der Flammenbeleuchtung," Ber. d. Deutsch. Chem. Ges., 31, 1898, p. 5) showed that the Welsbach mixture did not radiate more than a black body at the same temperature, and that there was, therefore, no necessity to assume that it was luminescent. A tube of arc lamp carbon which could be heated electrically to over 2,000°C. was used. Magnesia prisms were taken, and faces which met in a sharp edge coated with different substances—carbon, magnesia, thorium oxide, cerium oxide and Welsbach mixture. The prisms were then heated in the tube, and the brightness of the two neighbouring surfaces compared by looking down the end. There was little difference. As the inside of the tube was almost closed, the radiation from its end was practically radiation from a black body, and there should have been little difference, provided that the radiation from the prism was pure temperature radiation. It would, however, have been otherwise had one of the substances been luminescent; hence it follows that the Welsbach mixture is not luminescent.

Killing had maintained that the high luminosity was due to catalysis, and Bunte took up and developed this idea. If platinum black is held over a gas jet, the issuing gas condenses in it and lights up immediately, although the platinum is only at the temperature of the room. A means of lighting the gas is founded on this. The platinum acts as a catalytic agent in facilitating the combination of the oxygen in the air with the coal gas. Bunte supposed that the Welsbach mixture has somewhat the same properties, that it causes the gases to combine more suddenly. A higher temperature is therefore produced, and this explains the increased luminosity. On this

theory the diminution of the intensity with time was due to some of the oxide being carried away by the gas and to some of it sintering with dust particles.

Catalysis is, however, not the true explanation, for Le Chatelier and Boudouard (C.R., 126, 1898, p. 1861) showed that when the Welsbach mixture was heated in an atmosphere of the gaseous products of combustion it radiated quite as well as in the Bunsen flame. And Nernst and Bose (Phys. Zs., 1, 1900, p. 289) proved the same result by heating filaments of the mixture electrically and in the Bunsen burner, and showing that the radiation was the same in both cases when the temperature was the same, the latter being measured by the electric resistance of the filament.

The question was finally settled in an article by Rubens; but the true reason for the high luminosity had previously been indicated by Le Chatelier and Boudouard (loc. cit.) and also by Nernst and Bose (loc. cit.). Le Chatelier and Boudouard first showed that the radiation of the Welsbach mixture was less than that of a black body at the same temperature. They then took a thermo-junction, the junction itself being disc shaped and of a diameter of 1·5 mm., and covered it in succession with Welsbach mixture, thorium oxide, cerium oxide, platinum, magnetic iron oxide, uranium oxide and lanthanum oxide, and placed it each time in the same part of the same Bunsen flame. The temperature was then read by the thermo-junction and the brightness compared by means of a spectrophotometer with that of melting platinum for points in the red, green and blue. The results are given in the following table, the brightness of melting platinum being taken as 100 in each case:—

——	Temperature.	Red.	Green.	Blue.
	Deg. Cent.			
Welsbach mixture	1,380	7·0	12·5	12·5
Thorium oxide.....	1,290	1·45	1·4	0·3
Cerium oxide	1,110	1·9	0·7	0·15
Platinum	1,290	8·5	4·0	1·4
Magnetic iron oxide.....	1,080	1·5	0·48	0·1
Uranium oxide.....	1,070	0·30	0·25	0·05
Lanthanum oxide	1,250	4·0	3·1	1·8

Two striking facts are brought out by this table. First of all the Welsbach mixture attains a temperature 300 deg. higher than a similar black body placed in the same circumstances, for magnetic iron oxide is approximately a black body. Then the relative brightness of the Welsbach mixture increases from red to blue, while it decreases for all the other substances. This high emission in the blue is also brought out by the measurements of Nernst and Bose.

Now the substance in the flame is in a state of thermal equilibrium. It receives, mainly by conduction, a certain fixed quantity of heat per second, and loses it by radiation. The quantity radiated increases with the temperature. Since the temperature of equilibrium of the Welsbach mixture is so much higher than that of magnetic oxide, the Welsbach mixture must radiate very much less when the latter is at the same temperature. In comparison with the other substances, the radiation of the Welsbach mixture falls off as we enter the infra-red. We are, therefore, led to the conclusion that the high luminosity of the Welsbach mantle is due to the fact that it radiates less than the other substances in the infra-red.

In the article above referred to, Rubens ("Uber das Emissionsspektrum des Auerbrenners," Ann. d. Phys. (4), 18, 1905, p. 725) took a complete energy curve (*a*) of a new Welsbach mantle, the glass funnel being removed to avoid absorption in the glass. The mantle was suspended from above in order to eliminate the radiation from the stick in the centre. About 70 points were taken on the curve. The apparatus used was a mirror spectroscope with thermopile; the prisms were of fluorite and sylvin. Then an energy curve (*b*) of the Bunsen alone was taken, and finally the energy curve (*c*) of a mantle that had been dipped in ink and thus covered with a thin layer of iron oxide. When heated in the Bunsen flame the latter mantle reached only a bright red heat. The three curves are given in Fig. 7.

The carbon dioxide bands at $2{\cdot}8\mu$ and $4{\cdot}4\mu$ are very prominent. From the curves it is evident that the mantle is practically transparent to the radiation of the Bunsen flame. Hence, by subtracting (*b*) from (*a*), we get the radiation from the mantle

alone. This is represented by curve (*d*), in which, for the sake of clearness, the vertical scale is taken twice as large.

Rubens then determined the ratio of the emission of the Welsbach mantle to that of a black body of the same form which was at the same temperature. The result is represented by the curve (*f*), and we see at a glance from this curve why it is that the luminosity of the mantle is so high. Taking the limit of the visible spectrum at 0·7μ, Rubens finds the radiant efficiency of the mantle to be 2 per cent. This 2 per cent. is, of course, extremely effective in producing the sensation of light, owing to there being so much of it in the blue and green.

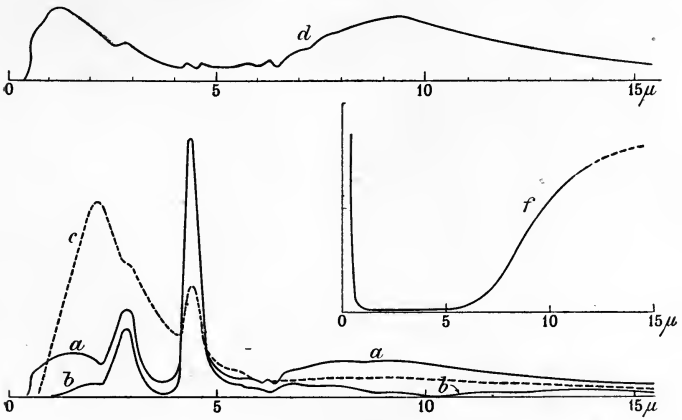


FIG. 7.

It is necessary that the proportion of thorium and cerium oxide in the mantle should be exactly right; if it is slightly varied the luminosity of the mantle becomes much less. In order to discover the reason for this, and at the same time to investigate the respective roles played by the two oxides, Rubens took an energy curve for (*g*) a mantle in which there was pure thorium oxide alone, and (*h*) a mantle in which there was pure cerium oxide alone. These two curves, together with (*a*), are reproduced in Fig. 8. The only appreciable difference between (*a*) and (*g*) is in the visible spectrum; the shape of (*h*) is, however, quite different, the radiation in the infra-red being much

greater than in the case of the other two curves. The addition of a little Ce_2O_3 to the ThO_2 seems, therefore, to move a maximum into the visible spectrum without affecting the rest of the curve, and to act in somewhat the same way as the sensitising bath in the photography of the red end of the spectrum, while the addition of too much Ce_2O_3 increases the infra-red emission and lowers the temperature.

In a later article ("Emissionsvermögen und Temperatur des Auerstrumpfs bei verschiedenem Cergehalt," Ann. d. Phys. (4), 20, 1906, p. 593) Rubens found that for the mantles he used the best proportion of Ce_2O_3 was about 0·8 per cent.

Le Chatelier and Boudouard (loc. cit.) found by comparing the brightness of some Welsbach mixture on their thermopile with the brightness of a mantle burning normally that the

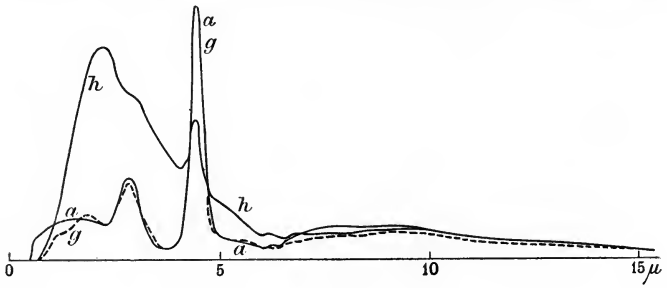


FIG. 8.

temperature of the latter was 1,650°C. In the first article, referred to above, Rubens stated that the average temperature of the mantle for which the curve (*a*) was given was 1,527°C. As objection was raised to the accuracy of this figure by Lummer and Pringsheim (Phys. Zs., 7, 1906, p. 89; p. 189), he made a further determination (Phys. Zs., 7, 1906, p. 186), placing the mantle at the centre of a hollow sphere, the inside of which was silvered, and measuring the "black" temperature of the radiation from a hole in the side. The maximum values then found for a number of mantles varied from 1,560°C. to 1,590°C. It is interesting to compare this result with a value obtained recently by one of Rubens' students (Hans Schmidt, "Prüfing der Strahlungsgesetze der Bunsenflamme," Ann. d. Phys.

(4), 29, 1909, p. 971) for the average temperature of the Bunsen flame itself 2·5 cm. above the edge of the burner. He obtained from about 1,597°C. for the centre to about 1,802°C. for the edge; this is in agreement with the fact that very fine platinum wire can be melted in the Bunsen. One of the previous best determinations had been that of W. J. Waggener (Ann. d. Phys. (3), 58, 1896, p. 579), who used thermopiles of different thickness and then extrapolated for an infinitely thin thermopile. His value was 1,785°C.

It is said that the diminution in intensity of the mantle with time is due to the cerium oxide volatilising more rapidly than the thorium oxide, and that, in order to counteract this tendency, makers are accustomed to put in rather too much cerium at first.

CHAPTER V.

THE CARBON GLOW LAMP.

The carbon glow lamp, which has now been on the market for 30 years, is associated principally with the names of Thomas Alva Edison and Joseph Wilson Swan. It consists, as is well known, of a carbon filament inside an exhausted bulb, the filament being heated to incandescence by the passage of an electric current. The bulb is exhausted for two reasons: first, to prevent chemical action between the carbon and the air, and second, to prevent loss of heat by conduction from the filament to the bulb, and thence to the outside atmosphere. The lamp would not be nearly so efficient if the bulb were filled with hydrogen, nitrogen or any other gas that does not react with carbon. This has been shown in an interesting investigation by L. W. Hartman ("The Conduction Losses from Carbon Filaments when heated to Incandescence in Various Gases," Phys. Rev., 20, 1905, p. 322). He mounted a glow lamp with a straight filament in front of a platinum oven, the temperature of which could be read by a platinum platinum-rhodium thermo-element enclosed in some magnesium oxide. The current in the lamp was then adjusted until the filament could not be seen against the magnesium oxide. The temperature of the filament was then assumed to be that given by the thermo-element, and the power supplied to the lamp determined for a range of temperatures. The experiment was next repeated with other lamps filled with hydrogen, carbon dioxide and nitrogen at atmospheric pressure. The results in the case of the carbon dioxide were not so good, owing to its reacting with the

filament; but the other two gases gave no trouble. As an example of the results obtained when the filament was maintained at 1,400 deg. abs. temperature, the watts, per centimetre of filament, supplied in the different cases were as follows, the Roman numerals referring to the lamp used :—

I., H	5·15	watts per centimetre.
I., CO_2	1·835	,,
II., CO_2	2·480	,,
III., H	5·90	,,
III., N	1·96	,,
III., Vacuum	0·81	,,

For the third lamp the difference from the last figure in the column must give the power lost by conduction. The radiation from a " black " filament of the same dimensions as the filament in III. was calculated to be 1·014 watts per centimetre.

Of course, the method used gives the " black " temperature of the filament, but only approximately.

As a material for films carbon possesses two great advantages: its ability to stand high temperatures and its high specific resistance. With these it possesses the disadvantage that after a time a black deposit forms on the inside of the bulb and diminishes the candle-power of the lamp. This deposit is due partly to carbon particles which have evaporated from the filament and partly to particles which have been shot off from it.

There are many different ways of preparing the filament. Natural fibres may be used, or a thread formed by squirting a viscous solution of cotton wool in zinc chloride through a hole in the side of a vessel. Before the filament is fixed in the bulb it is often subjected to a process called flashing. If it is rendered incandescent in an atmosphere of hydrocarbon gas, the heated filament decomposes the gas and a deposit of carbon is formed upon the surface of the filament. According to its treatment, the filament may have an appearance varying from sooty black to a grey or brilliant steel-like lustre.

In addition to the efficiency and life tests made on the photometric bench by practical men, a large amount of measuring has been done on glow lamps in physical laboratories. In flames, and in the case of the incandescent gas

mantle, one of the conditions is prescribed—namely, the temperature—but in the glow lamp the latter can be easily varied. It may also be assumed to be a definite function of the voltage. The current, voltage and radiation can be easily measured. It is, therefore, not to be wondered at that different people have sought to establish laws connecting these quantities. For example, a complete theory of the glow lamp has been worked out by H. S. Weber ("A General Theory of the Glow Lamp," Phys. Rev., 2, 1894, p. 112 and p. 197). Then we have the result of Prof. A. Jamieson that the candle-power is proportional to the sixth power of the voltage, and certain relations deduced by Abney and Festing ("An Investigation into the Relations between Radiation, Energy and Temperature," Phil. Mag. (5), 16, 1883, p. 224). Such results, however, are usually correct only for a limited range, and it is better to state results by comparison with the perfectly black body, which, of course, had not been realised experimentally when these investigations were carried out.

The carbon filament may, then, be regarded as an approximation to the perfectly black body. For any wave-length and temperature it will always radiate less than the latter; but, like the latter, when the temperature is increased, the maximum of the energy curve moves towards the visible spectrum, while the intensity increases at every wave-length in the visible spectrum, the increase being much more rapid at the shorter wave-lengths. This latter fact has been brought out by quite a number of spectrophotometric researches. The following figures, for example, are taken from an article by

——	16 c.p. carbon.				25 c.p. tantalum.				30 c.p. Nernst.			
Volts	120	100	90	82	120	100	90	82	120	100	92	90
Amperes	0·59	0·48	0·43	0·38	0·35	0·30	0·28	0·26	0·34	0·22	0·17	
Intensities: 459 $\mu\mu$.	1·82	0·49	0·26	0·12	1·46	0·61	0·35	0·20	2·47	0·32	0·10	Lamp goes out
488 ,, ...	1·76	0·53	0·28	0·15	1·39	0·62	0·36	0·20	2·35	0·32	0·10	
523 ,, ...	1·73	0·54	0·29	0·15	1·33	0·62	0·36	0·21	2·24	0·34	0·17	
570 ,, ...	1·73	0·56	0·32	0·16	1·31	0·63	0·38	0·22	2·04	0·37	0·18	
638 ,, ...	1·71	0·57	0·33	0·17	1·31	0·68	0·41	0·26	2·01	0·38	0·19	
760 ,, ...	1·60	0·59	0·37	0·20	1·22	0·72	0·47	0·30	1·82	0·42	0·23	
Mean intensity.	1·72	0·55	0·31	0·16	1·34	0·64	0·39	0·23	2·16	0·36	0·17	

P. Vaillant, the figures from the same source for the tantalum and Nernst lamps being added for the sake of comparison ("Sur les variations avec la temperature des spectres d'émission de quelques lampes electriques," C.R. 142, 1906, p. 81). For each wave-length the intensity of each lamp at its normal voltage is taken as unity. The normal voltage of each lamp was 110 volts.

If the three lamps are compared at their normal voltage, their mean intensities being made equal, we have

	λ in μμ	459	488	523	570	638	760
Intensity	Carbon	1·00	1·00	1·00	1·00	1·00	1·00
	Tantalum	1·28	1·17	1·03	0·94	0·78	0·62
	Nernst	0·92	1·07	1·04	1·03	1·02	0·91

The similarity of the carbon filament with the black body, however, must not be pushed too far. E. L. Nichols ("The Visible Radiation from Carbon," Phys. Rev., 13, 1901, pp. 65 and 129) made a spectrophotometric investigation of carbon rods which were heated by an electric current *in vacuo*, the temperatures being read by thermo-junctions embedded in the rods and extrapolation to an infinitely thin thermo-junction, and he found that above 1,100°C., relatively to the other colours on both sides, the intensity of the yellow increased much more rapidly than it ought to have done had the law of the black body been followed. This was the case both with untreated carbons with black surfaces and with treated carbons with grey surfaces. The carbons exhibited, therefore, a slight selective emission. This fact has been confirmed by Blaker (Ernest Blaker, "A Spectrophotometric Comparison of the Relative Intensity of Light from Carbon at Different Temperatures," Phys. Rev., 13, 1901, p. 345) by observations on ordinary carbon glow lamps.

No complete normal energy curves have been published for a carbon filament such as is used in a glow lamp. The obvious difficulty is the glass of the bulb, which absorbs the infra-red beyond 3·0 μ. Prismatic energy curves of a glow lamp at different voltages, taken with a glass prism and linear thermo-pile, have been given by Abney and Festing ("The Relation

between Electric Energy and Radiation in the Spectrum of Incandescence Lamps," Proc. Roy. Soc., 37, 1884, p. 157), and normal energy curves have been given by Nichols, who also used a glass prism and thermopile ("The Distribution of Energy in the Spectrum of the Glow Lamp," Phys. Rev., 2, 1894, p. 260). Such curves have, however, not so much value, because—as I know from experience—the glass in the spectroscope begins to distort the curve a considerable way before the glass of the bulb makes itself felt.

If we wish, therefore, to study the distribution of the energy of radiation of glowing carbon from end to end of the spectrum, we must refer to an article by Paschen ("Uber Gesetzmässigkeiten in den Spectren fester Körper," Ann. d. Phys., 60, 1897, p. 662), which gives figures for a piece of platinum foil coated with lamp-black, for three pieces of graphitic carbon in an exhausted glass bulb with a fluorite window, and, finally, for one of these pieces of carbon taken out of the bulb and radiating in the free atmosphere. The temperature was taken by a thermo-junction embedded in the carbon or placed in the fold of the platinum foil. Two prismatic energy curves are also given by K. Ångström ("Energy in the Visible Spectrum of the Hefner Standard," Phys. Rev., 17, 1903, p. 302) for a straight filament inside a glass bulb with a fluorite window. He shows that within the visible spectrum they can be represented by Wien's law, the black temperature of the normal voltage being 1,730°C. The true temperature should thus be higher.

In the articles above referred to, Nichols was not able to measure the temperature of his carbon rods above 1,500°C. owing to the carbon combining with the metals of the thermo-element. Paschen in his experiments did not go above 1,300°C. There seems to be thus little prospect of measuring the temperature in a filament directly. On the assumption that the radiating properties of the filament lie between those of the perfect black body and of platinum, Lummer and Pringsheim ("Temperaturbestimmung fester glühender Körper," Verh. d. Deutsch. Phys. Ges., 1, 1899, p. 230) found 1,825°C. and 1,600°C. as the limits of its normal temperature. The method used was that of determining the

position of the maximum of the energy curve. Le Chatelier ("Sur la mesure optique des températures élevées," Journal de Physique (3), 1, p. 185) gives the following table, showing the increase of temperature of a 10-volt carbon lamp with the diminution of its resistance :—

Temperature.	Resistance.
15°C.	1·00
700°C.	0·75
1,000°C.	0·66
1,400°C.	0·57
1,800°C.	0·49
2,100°C.	0·44

He states that 1,800°C. is the temperature of glow lamps at their usual brightness, and that they can be overrun to 2,100°C. These results are obtained with his optical pyrometer by comparing the brightness with that of a standard lamp. The pyrometer uses only the red rays, the rest being cut out by red glass. Le Chatelier makes no correction for the "blackness" of a body. His values, therefore, should be somewhat low.

The temperatures of a carbon lamp and a metallised carbon lamp have recently been determined very carefully by A. C. Jolley ("Modern Incandescent Electric Lamps," THE ELECTRICIAN, Vol. LXIII., pp. 700 and 755) for different voltages. He used Stefan's law and three different empirical formulæ. He obtains 1,617°C. as a mean value for the carbon, and 1,676°C. as a mean value for the metallised carbon lamps at their normal voltages. I cannot help feeling that these values are too low. Stefan's law gives, of course, a lower limit, the black body temperature, and I think the true temperature should differ more from the Stefan's law temperature than Jolley's values do. But we shall never reach finality in this matter until we place the filament inside an enclosure, the inside surface of which is a mirror, and examine the radiation through an aperture. Then the black body temperature of the aperture will be the true temperature of the filament.

The efficiency of glow lamps has been determined by the calorimetric method by Merritt ("Some Determinations of the Energy of the Light from Incandescent Lamps," Ernest

Merritt, Amer. Journ. of Sc. (3), 37, 1889, p. 167) and by Russner ("Uber die Licht und Wärmeenergie von Glühlampen," Johannes Russner, Phys. Zs., 8, 1907, p. 120). In Merritt's experiments the glow lamp was placed in a large glass calorimeter, through which a steady flow of water was maintained. From the quantity of water which passed through in a given time, and the difference in its temperature before entering and after leaving, the amount of dark heat absorbed by the water in the calorimeter in that time could be measured. The radiation from the lamp after passing through the water and glass of the calorimeter was allowed to fall on a thermopile and the deflections of the galvanometer noted. A small cell containing an opaque solution of iodine in carbon disulphide was then placed between the pile and the lamp and the deflection again observed. The ratio of the second deflection to the first, therefore, gave the ratio of the dark heat escaping from the calorimeter to the total radiant energy escaping. It was found that a little less than one-third of the energy that had passed through the glass and water of the calorimeter was dark heat. It was also found photometrically that from 25 to 30 per cent. of the light of the lamp was absorbed by the calorimeter. Hence the total amount of dark heat radiated could be calculated. The energy supplied to the lamp was determined electrically, and as the difference of these two quantities gave the light radiated the efficiency could be determined. The value found for the lamp experimented on was 3·6 per cent. for its normal voltage.

Merritt made further determinations, letting the rays from different lamps fall on a thermopile with and without an alum filter in front of it. He corrected for the light absorbed and the dark heat transmitted by the filter in the same way as before. By this method he obtained higher values.

In Russner's determinations the brass cap and plaster were removed from the lamp, and the latter was suspended in a beaker filled with a solution of ferrous ammonium sulphate. This liquid, as he was the first to point out, is almost colourless, and absorbs the heat rays much better than water. The current was run for a measured interval, the solution stirred and the rise of temperature noted. The bulb of the lamp was

then covered with tinfoil, again immersed in the solution and the rise of temperature for the same interval of time noted. It was greater in this case, as the light also was absorbed. The difference of the two readings divided by the second gave the efficiency. Russner apparently did not correct for the light absorbed by the solution in the first case. He gives results for two lamps—0·58 and 0·61 per cent.

As has been mentioned in the first of these studies, a filter of water or any other solution is an unsatisfactory way of separating dark heat from light.

The first determination to which exception cannot be taken on the point of principle is due to C. E. Mendenhall (" On the Luminous Efficiency of the Carbon Filament," Phys. Rev., 20, 1905, p. 160), who used a modification of Ångström's method. For a 100 c.p. lamp he obtained the following figures :—

Watts input.	Efficiency.	Watts input.	Efficiency.
61·0	2·38%	75·5	2·63%
65·5	2·39	78·0	2·70
70·5	2·45	81·5	2·93
70·75	2·47		

Normal brilliancy corresponded to about 75 watts input, for which the efficiency was 2·6 per cent.

I have determined the radiant efficiency of two 250-volt lamps (" The Efficiency of Metallic Filament Lamps," Roy. Soc., Edin., Proc. 30, p. 555, 1910) by the method described in the first of these studies. The results are as follows :—

——	Lamp I.		Lamp II.	
Volts.	Amperes.	Radiant efficiency.	Amperes.	Radiant efficiency.
116	0·132	0·12%	...	...
184	0·173	1·40	0·163	0·72%
216	0·213	1·97	0·194	1·48
250	0·257	3·42	0·241	2·42
270	0·258	3·95	0·268	3·43

The mean value for the normal voltage is thus 2·9 per cent.

It is interesting to note that the efficiency has been found to vary considerably with the nature of the surface of the

filament. Thus Evans ("Observations on the Radiation of Light and Heat from Bright and Black Incandescent Surfaces," Proc. Roy. Soc., 40, 1886, p. 207) flashed two perfectly similar filaments, one in an atmosphere of ordinary cold coal gas and the other in very hot hydrocarbon vapour. The first took on a permanent coating resembling lamp-black; the second had a bright silvery appearance. The blackened filament required 100 watts in order to give 20 c.p., while the filament with a bright surface gave an equal light with 74 watts, the difference being apparently due solely to the radiating properties of the surface. Similar results have been obtained by E. L. Nichols ("The Distribution of Energy in the Spectrum of the Glow Lamp," Phys. Rev., 2, 1894, p. 260).

W. Wedding found 3·5 and 3·9 per cent. for the radiant efficiencies, and 0·19 and 0·335 per cent. for the luminous efficiencies of two carbon lamps which he investigated. He used a bolometric method, by which he was able to determine the absolute value of the energy received per square centimetre of bolometer surface, and he separated the dark heat from the light by means of a water filter. The radiant efficiency is, of course, the ratio of light to total energy radiated, and the luminous efficiency the ratio of light to total energy consumed. It is in the highest degree striking that Wedding's results for these two quantities should differ so widely, and one cannot avoid the suspicion that there was some error made in determining the absolute value of the energy received. According to Wedding, the total energy radiated is only about one-fifteenth of the electrical energy consumed. Where does the difference go to? It must be lost by convection and conduction. Now other experimenters are accustomed to regard this loss as small. Drysdale ("On Luminous Efficiency and the Mechanical Equivalent of Light," Proc. Roy. Soc., A 80, 1907–08, p. 19) states that he convinced himself that it was not more than 2 or 3 per cent. of the total energy consumed.

Let us consider the question of this convection loss more closely. The filament is losing heat only by radiation. Hartman's measurements (loc. cit.) leave no room for an appreciable convection loss to the bulb, and since the filament is of the same brightness to its ends, there is no appreciable con-

duction loss along the leading-in wires. When the radiation reaches the bulb the longer waves are absorbed, since glass absorbs beyond 3·0 μ. As we know neither the exact absorption coefficient of the glass nor the exact shape of the energy curve of the filament, we cannot tell what fraction of the radiation is absorbed, but shall probably not be far wrong in guessing it at a third.* This absorbed energy is spent in heating the glass, and is lost from the glass by conduction, convection and radiation. Now the transference of energy byr adiation from one body to another varies with the difference of the fourth or higher powers of their temperatures; the transference of energy by conduction varies with the difference of the first power. Hence, as the glass is not much above room temperature, the energy it absorbs is lost mainly by conduction and convection. Hence the calorimetric methods, if it were possible to carry them out accurately, should give the luminous efficiency, while the methods adopted by Mendenhall and myself give the radiant efficiency.

Abney and Festing (" The Relation between Electric Energy and Radiation in the Spectrum of Incandescence Lamps," Proc. Roy. Soc., 37, 1884, p. 157) found for a carbon lamp that the watts consumed were not proportional to the total radiation measured by a thermopile, but to the latter plus a constant. For small currents the radiation increased slowly, but afterwards more rapidly. As they stated that there was no appreciable convection loss—a statement to which Sir William Siemens took exception—they put the difference down to energy consumed in molecular rearrangement in the filament. It is, however, quite clear that the difference is radiation absorbed by the bulb and lost from the latter by conduction and convection.

* *Cf.* Table on p. 63, which became known to me only after the above was in type.

CHAPTER VI.

THE ARC.

If two carbon rods are connected with the terminals of a battery of storage cells, so that their difference of potential is about 80 volts, and if the ends of these rods are pushed together and then drawn apart, a bright discharge characterised by intense light and heat passes from the one carbon to the other. This is the electric arc, which dates from the beginning of last century. It has been the subject of a great number of investigations, but its phenomena are extremely complicated and by no means yet fully understood.

If an image of the arc is thrown on a screen by a lens and examined, it is found that the extremities of the carbons, although similar to begin with, soon begin to show differences. The end of the positive carbon becomes hollowed out into a crater-like depression, while the end of the negative terminal becomes pointed. Both the carbons are consumed by the arc, the positive one twice as fast as the negative. Much the greater portion of the light comes from the positive electrode, less from the negative, and very little from the space between the carbons. The latter is filled with an egg-shaped violet-coloured vapour, which seems to spring from the crater, surrounded by a blue layer which is, in its turn, surrounded by yellowish flames.

It has been shown that if V denotes the P.D. between the terminals and l the length of the arc, the relation

$$V = m + nl$$

holds, m and n being quantities that vary with the current. For carbon electrodes in air at atmospheric pressure, m is about

39 volts. If metal electrodes are used, m varies with the metal, being less the lower the temperature of volatilisation of the metal. Hence the product of m and the current probably roughly represents the rate at which work is done in volatilising the metal. There is a considerable fall of potential in the arc close to the anode, a smaller one close to the cathode and a gentle potential gradient in the intervening space.

If the current becomes too large the P.D. between the electrodes falls, becoming constant for further increase of current, and the lamp begins to hiss. Hissing is caused by the crater becoming too large to occupy the end only of the positive carbon and by its therefore extending up the side.

Besides the P.D., length and current, the nature of the arc depends on the material and shape of the carbons, the ballast resistance in the circuit, and the nature and pressure of the gas in which it burns. It would lead too far, however, to study the influence of these factors, and we shall proceed to consider the arc as an energy transformer.

It receives energy from two sources: (1) work done by the current, and (2) heat of combustion of the carbons. The latter may be neglected in comparison with the former. In the case of an arc experimented on by L. B. Marks ("The Enclosed Arc Light," THE ELECTRICIAN, Vol. XXXVIII., p. 615, 1896), which may be regarded as typical, the power consumed in watts was 498·69, the carbons were 11·11 mm. in diameter, the consumption of positive carbon was 11·556 mm. per hour, and the consumption of negative carbon 8·077 mm. per hour. If we take the density of the carbons as 2·2 grammes per cubic centimetre, the mass consumed per second is

$$\frac{\pi \times 1{\cdot}111^2 \times 1{\cdot}9633 \times 2{\cdot}2}{2^2 \times 60^2} \text{ grammes.}$$

I have not been able to find the heat of combustion of arc carbon, but it is probably less than the value for coke, which is 6,900 calories per gramme. Hence, owing to the combustion of the carbons, less than

$$\frac{\pi \times 1{\cdot}111^2 \times 1{\cdot}9633 \times 2{\cdot}2 \times 6{,}900 \times 4{\cdot}2}{2^2 \times 60^2} = 3{\cdot}47 \text{ joules}$$

are liberated per second, and this is small in comparison with 498·69.

The arc loses energy by conduction, convection and radiation. I know of no data on the conduction and convection losses; they must be large. Owing to the way the carbons heat up, much dark heat must be radiated from the whole of their surface. Light is radiated only from their poles.

The temperature of the poles is of interest. Sir Wm. Abney stated in 1881 that with given carbons the brightness of the crater is constant, being apparently due to the temperature at which carbon vaporises. It by no means follows that the light we receive from each square millimetre of crater surface is constant, as some may be absorbed by the vapour of the arc. By the photometric method already described, Le Chatelier found 4,100°C. for the positive carbon for all lamps, no matter what the current was, and 3,000°C. for the negative carbon ("Sur la mesure optique des températures élevées," Journal de Phys. (3), 1, pp. 185-205, 1892). Violle determined the temperature by an original method (J. Violle, "Sur la temperature de l'arc electrique," Comptes Rendus, 115, pp. 1273-1275, 1892. "Lumière et chaleur de l'arc," Journal de Phys. (3), 2, pp. 545-552, 1893). The carbon was filed away round about, a short distance from the end. As soon as the end attained its usual brightness it was knocked off by a light blow, fell into a water calorimeter and the heat given out was measured. To complete the determination we require to know the specific heat of carbon right up to its melting point. Violle found that a gramme of carbon gave out 1,600 calories in cooling from the temperature of the arc to 0°C. and that it gave out 300 calories in cooling from 1,000°C. to 0°C. Assuming that above 1,000°C. the specific heat had the theoretical value 0·52 calculated from Dulong and Petit's law, he obtained 3,500°C. for the temperature of the positive carbon. Le Chatelier ("Remarques sur la chaleur specifique du carbone," Comptes Rendus, 116, pp. 1051-1052, 1893) called attention to the fact that the specific heat was not constant above 1,000°C. Violle thereupon determined the specific heat of graphite above 1,000°C., heating it in an electric oven, determining its temperature photometrically and also calorimetrically by means of

a piece of platinum or iridium (" Chaleur specifique et point d'ebullition du carbone," Comptes Rendus, 120, pp. 868-869, 1895). He found the temperature of volatilisation of graphite to be 3,600°C.

Lummer and Pringsheim find that the maximum of the energy of the arc lies at 700$\mu\mu$. Its temperature, therefore, is 3,480°C. if it radiates like platinum, or 3,930°C. if it radiates like the perfect black body (Verh. deutsch. phys. Ges., 1, pp. 215-235, 1899). This result, of course, refers to the anode, as much the greater proportion of the light comes from there, probably 85 per cent.

Only one determination has been made of the radiant efficiency of the arc, that of H. Nakano, described by Mrs. Ayrton in " The Electric Arc," p. 369. He used a water filter method, similar to Merritt's, and found that with various kinds and sizes of carbons the value varied 1·8 to 19·8 per cent. The 45 tests he made gave an average value of 10 per cent. His method would give a result considerably too large. If the arc were a perfectly black body at the temperature of the crater obeying Wien's radiation law, its radiant efficiency should be about 30 per cent.

Data for a prismatic energy curve have been given by Langley (Phil. Mag. (5), 29, 1894, p. 51).

Within recent years the arc has been improved in three directions. First of all the carbons have been enclosed in a globe which fits tightly and restricts the supply of air. This lengthens the life of the carbons and diminishes the cost for attendance. It should also diminish the convection energy loss. Of course, at the same time light is absorbed by the globe. If the glass is clear at least 10 per cent. of the total light is absorbed, and if it is ground at least 20 per cent. Then the carbons have been mounted inclined to one another, with the poles pointing downwards instead of coaxially, and the efficiency of the arc has been increased by impregnating them with different substances giving a coloured flame.

It is easy to see the advantage gained by having the carbons inclined to one another with the arc passing between the lower ends: the crater is no longer obscured by the negative carbon. The light given by the ordinary arc varies in different direc-

tions, and it has been shown that for any direction it is proportional simply to the amount of crater visible in that direction multiplied by the cosine of the angle between the direction and the axis of the carbon. If the negative carbon is placed at the side, the crater still forms on the end, and its light is not appreciably absorbed by the negative carbon.

In the pure carbon arc the arc itself contributes a very small proportion of the light. We are here dealing with the temperature radiation of a solid body, the positive carbon, the case being analogous to the candle flame and the glow lamp, the radiating substance being solid carbon and the main difference one of temperature. But in the arc in which the carbons are impregnated with chemicals, the flame arc, conditions are different. Here the bulk of the light is given by the flame, by the calcium oxide, or whatever the impregnating substance is, and we are probably not dealing with temperature radiation.

There are no data on the luminous or radiant efficiency of the flame arc.

CHAPTER VII.

THE NERNST LAMP.

Previous to the Nernst glower, attempts had been made to construct electric lamps in which the illuminating body consisted of earths. For example, in 1877, Jablochkoff took out a patent for a lamp in which a body of kaolin and similar refractory earths conducted electricity when it was heated to a certain temperature. On account of its low efficiency and the necessity for very high tension currents, this lamp proved a failure, and it was not until Prof. Nernst brought forward his lamp in 1898 that work on this line became successful.

The Nernst glower, which seems to have been suggested by the Welsbach mantle, is a combination of the oxides of cerium, thorium and zirconium—a rather obvious combination. In a lecture by Nernst (Elektrot. Zs., 20, 1899, pp. 355-356) describing it, it is, however, described as containing magnesia. The conduction in the glower is electrolytic (Nernst, Zs. für Electrochemie, 6, 1899, p. 41); hence one would expect it to be more suitable for alternating than direct current, but, as a matter of experience, it does better on direct. Probably the oxygen of the air depolarises it and prevents electrolysis. The glower conducts only when heated. In the first lamps it had to be heated with a match or spirit lamp before it would light up, but the lamps were soon provided with an arrangement which heated the glower until it conducted and then automatically cut out. As the resistance of the glower diminishes rapidly with increase of current, it is liable to burn through, and hence it is run in series with a ballast resistance, usually of iron, on account of the high positive temperature coefficient

of the latter. If the current increases 5 per cent. the resistance of the iron wire increases 75 per cent.

On its introduction it was thought that the Nernst glower would supersede the carbon filament. It did not require to be placed in an evacuated globe, and it gave $1\frac{1}{2}$ times as much light for the same electrical energy. But although very many types in succession have been placed on the market—for a description of which see the article by J. Stöttner (Journal of Elec. Eng., 32, 1902-03, p. 520)—the success of the lamp has by no means come up to expectations, and it is not widely used. This is due to the advent of the metal filament lamp, and possibly also to the uncertainty of the life of the filament. For although they are supposed to last about 400 hours, and some last more than 1,000 hours, yet others go very much sooner owing to failure of the flex, fracture of the glower or faulty action of the heating coil.

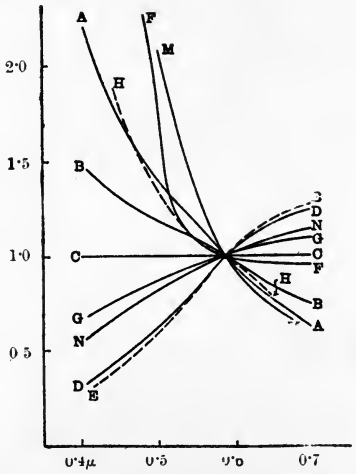
After burning a long time the glower crystallises. The precise cause of this is not known, but it is supposed to be due to electrolysis.

The light of the glower has been examined several times with the spectrophotometer. The figures obtained by P. Vaillant have already been given in connection with the carbon glow lamp. A more thorough study has been made by L. W. Hartman ("A Spectrophotometric Study of the Luminous Radiation from the Nernst Lamp Glower under Varying Current Density," Phys. Rev., 17, p. 65, 1903). The following diagram (Fig. 9), comparing the radiation from a Nernst glower at its normal current strength with various other sources of light, is taken from Hartman's Paper. Thus, at its normal current strength, the glower is strong in the red end of the spectrum, which, of course, might have been inferred from its colour.

The temperature of the glower has been determined directly by Hartman ("Concerning the Temperature of the Nernst Lamp," Phys. Rev., 22, p. 351, 1906). Three specimens of the same platinum and platinum-rhodium wire used by Nichols in his determination of the temperature of the acetylene flame were made into thermo-junctions. The junctions were brought into contact with the glower and the temperatures

read. The results were then plotted as a function of the radius of the wire, and by continuing the curve to cut the axis of zero radius the temperature that would be read by an infinitely thin junction was found. The temperatures of six glowers under normal conditions varied from 1,505°C. to 1,535°C. Of course, this method is here not nearly so suitable; the thermo-junction is not small in comparison with the filament, although small in comparison with the acetylene flame. Hence the curve of temperature may change its gradient considerably before meeting the axis of zero radius.

Lummer and Pringsheim (Verh. deut. Phys. Ges., 3, p. 36, 1901) had previously shown from the position of the



A, Acetylene in Oxygen. B, Acetylene-Hydrogen in Oxygen. C, Acetylene in Air. D, Kerosene Lamp. E, Ordinary Gas Flame. F, Fresh Lime Light. G, Old Lime Light. H, Arc Light. M, Magnesium Light. N, Nernst Lamp.

FIG. 9.

maximum that the temperature of the glower was 2,450° abs. if it radiated as a black body and 2,200° abs. if it radiated like platinum. Mendenhall and Ingersoll (Phys. Rev., 24, p. 230, 1906) find the normal temperature to be 2,300° abs. They compared the emission of the glower with a comparison lamp for a particular wave-length in the visible spectrum when the glower was at the melting points of gold and platinum.

Then, assuming that Wien's law holds, they were able to determine the temperature for any given brightness.

But by making a very thorough study of the energy curve of different glowers for different consumptions of energy, W. W. Coblentz has recently shown ("Selective Radiation from the Nernst Glower," Bull. Bureau of Standards, 4, p. 533, 1908) that the Nernst glower, like the Welsbach mantle, behaves very unlike a black body. The apparatus was a mirror spectroscope with fluorite prism and bolometer. It was enclosed, the slit being covered with a plate of fluorite, and inside it were placed vessels containing phosphorous pentoxide and sticks of potassium hydroxide. In front of the slit was placed a water-cooled shutter, and the glower was placed close to the shutter. By this arrangement the bands of water vapour and carbon dioxide were entirely eliminated from the emission curves.

At the rated voltages the energy curves were somewhat similar to those of a black body. On decreasing the temperature discontinuities appeared which were at first attributed to faults in the apparatus. But when a glower was run on a 2,000-volt transformer which permitted a low heating, the colour then being a reddish grey, the curve decomposed into a number of separate bands. Fig. 10 gives the curves then obtained for 2·0, 7·1 and 10·6 watts. The results are quite different from what previous work would lead us to expect. The change in relative intensity of the two groups of bands with the temperature is very interesting.

By integrating the energy curve, Coblentz deduced values for the radiant efficiency varying from 3·6 to 7·4 per cent., but does not state which corresponds to the rated voltage. The most careful determinations of the radiant efficiency have, however, been made by L. R. Ingersoll ("On the Radiant Efficiency of the Nernst Lamp," Phys. Rev., 17, p. 371, 1903), who used Ångström's method. According to his results, glowers are by no means uniform. New ones at their rated voltage show a radiant efficiency of from 4·35 to 4·70 per cent., the mean being 4·61 per cent. It falls rapidly for about the first 20 hours, decreasing to 4·3 per cent., and varies only slowly after this. Some very old glowers gave results of

3·6 per cent. His figures are for 110-volt glowers consuming 89 watts.

In Drude's " Optics," p. 447, first German edition, it is stated that the luminous efficiency of the Nernst glower is 12 per cent. The reference to the determination is not given and the result is obviously too high. The luminous efficiency should differ

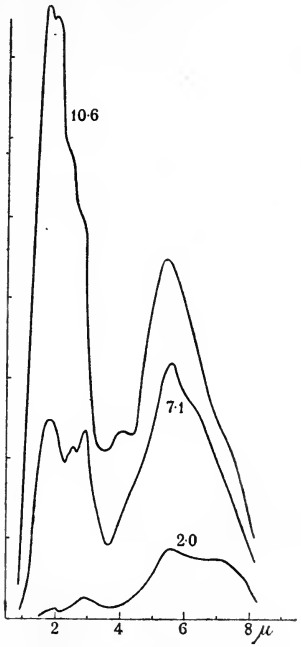


FIG. 10.

more from the radiant efficiency than in the case of the glow lamp, as the lamp is not evacuated and the conduction and convection losses are hence important.

Wedding finds 0·848 and 6·4 per cent. respectively for the luminous and radiant efficiencies.

CHAPTER VIII.

METAL FILAMENT LAMPS.

The metal filament glow lamp is the oldest form of glow lamp, and dates from before the carbon filament. Edison, for example, devoted a considerable amount of attention to a lamp in which a thin platinum wire, raised to incandescence by the passage of an electric current, formed the illuminating body. The platinum lamp, however, was never a commercial success, because the temperature of platinum has to be raised very nearly to its melting point in order to produce light economically, and hence, if the voltage increased above its normal value, the filament burned through.

The success of the carbon lamp stopped experimenting in metallic filament lamps for a considerable time, and, although an iridium lamp was patented in 1890, it was not until 1898 that the first commercial metal filament lamp appeared. This was the osmium lamp, invented by Auer von Welsbach, in which the filament was made of metallic osmium, and which was much more efficient than the carbon lamp, giving a candle for $1\frac{1}{2}$ watts.

The osmium lamp began to be regularly supplied in 1902. In 1905 the tantalum lamp appeared on the market. It was not so fragile, but slightly less efficient. It was followed by the tungsten lamp. All the various metal filament lamps on the market, with the exception of the tantalum lamps of course, are made of tungsten. The osmium lamp is now no longer made; it is less efficient than the tungsten lamp, and the quantity of osmium available is limited.

The original method of manufacturing the Osram lamp, which was the first tungsten filament lamp on the market, is

described in a paper by H. Hirst ("Recent Progress in Tungsten Metallic Filament Lamps," Journal of Elec. Eng., 41, 1908, p. 636). A paste of the consistency of putty is prepared from the metal in a finely divided form, together with some binding or stiffening agent. It is then squirted through a very fine orifice in a diamond with a pressure of several tons per square inch. The filaments thus formed are heated in air, when they become more coherent. They are then sintered by the passage of an electric current, the sintering being carried out in gases which attack the binding agent, so that finally a filament of pure metallic tungsten remains. This method is, however, now obsolete; tungsten filaments are now being drawn and are consequently very much stronger than formerly.

The specific resistance of osmium, tantalum and tungsten is, of course, considerably less than the specific resistance of carbon. Consequently the filament must be made longer and its diameter less. For example, in the case of a 120-volt Osram lamp, taking 0·20 to 0·25 amperes, the diameter of the filament is 0·03 mm.

All three metals possess a high positive temperature coefficient of electrical resistance. In the paper already cited, the following figures are given as the ratios of the resistances of the different filaments at those temperatures, which in a vacuum correspond to 1·5 watts per candle, to their resistances when cold;—

For a carbon filament	0·55
For a tantalum filament	5·70
For an osmium filament	8·50
For a tungsten filament	11·0

The normal burning temperatures of metal filament lamps have been determined by C. W. Waidner and G. K. Burgess ("Preliminary Measurements on Temperature and Selective Radiation of Incandescent Lamps," Bull. Bureau of Standards, 2, p. 319) by an optical pyrometer. The results are given in the table on page 61, the normal burning temperatures of three carbon lamps being added for the sake of comparison. The last column, giving the approximate values of the actual temperatures, is obtained by adding to the black-body temperature for blue light twice the difference between the red

Type of lamp.	Watts.	Volts.	Observed black body temperature (red).	Approximate true temperature.
Carbon	4·0	50	1,710°C.	1,800°C.
,, ...	3·5	118	1,760°C.	1,850°C.
,, ...	3·1	118	1,860°C.	1,950°C.
Tantalum	2·0	110	1,865°C.	2,000°C.
Tungsten	1·0	100	2,135°C.	2,300°C.

and blue readings, an empirical relation found to hold fairly well for platinum for lower temperatures than those in the table. How far its application is justified here it is impossible to say. The "black" temperature of the melting point of tungsten, according to Waidner and Burgess, is about 2,900°C.

In the papers referred to in connection with the carbon glow lamp ("Modern Incandescent Electric Lamps," THE ELECTRICIAN, Vol. LXIII., pp. 700 and 755), A. C. Jolley finds about 1,700°C. and 1,800°C. respectively for tantalum and tungsten filaments at their normal voltage. Here the temperature, as determined by Stefan's law, is very much lower.

It should be noticed that Jolley misquotes the results of Waidner and Burgess, making them deg. abs. instead of deg. cent.

The following diagram is taken from a paper by Coblentz ("Radiation Constants of Metals," Bull. Bureau of Standards, 5, p. 339, 1909). It represents the energy curves of (*a*) an untreated carbon filament, (*b*) a flashed carbon filament, (*c*) a tungsten filament, and (*d*) an osmium filament, the voltage of each lamp being regulated so that all gave the same colour and the curves then being plotted so as to coincide in the visible spectrum. The apparatus was a mirror spectroscope with fluorite prism, but the filaments were observed on through the ordinary glass bulbs; hence, owing to the absorption of the glass, the curves are not correct beyond $2{\cdot}5\mu$. A glance at the figure shows that the carbon lamps emit about one-third more infra-red energy than the metal filaments. To that, and to the higher temperature, the superior efficiency of the metal filament lamps is due.

By the method already described in connection with the carbon lamp, Russner determined the radiant efficiency of a

tantalum lamp, an osmium lamp and an osram lamp, and found respectively the values 2·2, 2·3 and 2·46 per cent. Wedding found 0·622 and 7·7 per cent. respectively for the luminous and radiant efficiencies of an osmium lamp.

I have recently determined the radiant efficiency of some metallic filament lamps (Proc. Roy. Soc., Edin., Vol. XXX., p. 555, 1909-10) by a method already described in the first of these studies. My results are given in the following table.

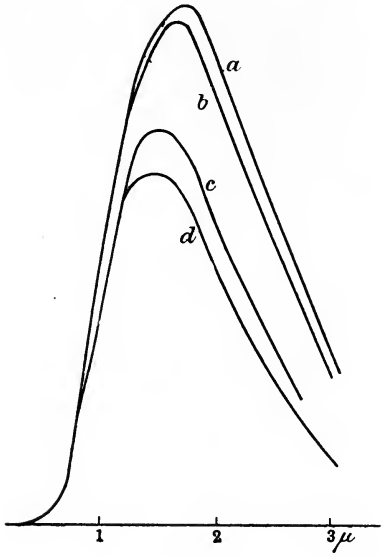


FIG. 11.

The marked voltage of the first two tungsten lamps was 250 volts, of the second two 130, of the tantalum 125 and of the osmium 50. The number in the bracket is merely my number for the lamp:—

Volts.	Tungsten (3).	Tungsten (4).	Volts.	Osmium (5).
116	...	2·48	30	2·17
184	4·96	5·98	45	3·84
216	7·42	9·02	55	6·52
250	7·60	9·39	...	...
270	8·06	9·59	...	...

Volts.	Tungsten (6).	Tungsten (7).	Tantalum (8).	Tantalum (9).
75·0	1·61	1·69	2·06	3·00
125·0	6·61	6·43	6·66	6·35
146·5	9·04	8·83	...	...
150·0	...	...	7·70	9·25

After this section was written, two papers by G. Leimbach, which deal with the efficiency of glow lamps ("Die Strahlungseigenschaften der elektrischen Glühlampen," Zs. f. wiss. Photogr. Photophysik u. Photochemie, 8, pp. 333-360 and pp. 365–380, 1910), came to my notice. Some of the principal results of these papers are given in the following table. The first column gives the name of the lamp, the second its watts per hefner candle, the third the ratio of total energy radiated to total energy supplied, the fourth the radiant efficiency and the fifth the luminous efficiency:—

1.	2.	3.	4.	5.
Carbon glow lamp	3·8	61·9%	2·85%	1·75%
Nernst	2·0	49·2	4·43	2·17
Tantalum	2·0	64·8	4·26	2·75
Osram	1·5	75·6	4·63	3·50
A.E.G. metal filament.....	1·7	80·5	4·41	3·55
Bergmann	1·7	68·5	5·03	3·44
Just Wolfram	1·7	72·2	4·44	3·20
Sirius colloid lamp	1·5	65·4	5·42	3·55

The total energy radiated was obtained by taking readings with a bolometer in different directions. The light was separated from the dark heat by means of a ferrous ammonium sulphate filter. The third column is especially valuable. It constitutes the only data on the convection and conduction loss of glow lamps which we have, with the exception of Wedding's, and the latter, as has been mentioned, seems unreliable.

CHAPTER IX.

THE MERCURY ARC.

The mercury arc lamp is one to which a considerable amount of attention has been given, and it is the subject of numerous patents. The best article on its history is by Von Recklinghausen ("Uber die Quecksilberdampf-lampe von P. C. Hewitt," Elektrot. Zs., p. 492, 1902). It has not been a commercial success, principally on account of its strong green colour, although it appears to be the most efficient lamp made, different observers having obtained one candle per half-watt from it ("Experiences de M. Cooper Hewitt sur les tubes à vide," Maurice Leblanc, Journ. de Phys., (4) 4, p. 416, 1905). It dates from 1860, Way (Chem. News., 2, p. 167, 1860) having produced it by letting a fine mercury jet fall from a reservoir into a vessel placed to receive it. The reservoir and vessel were connected to the poles of a battery; the electric current scattered the jet and between the drops an arc formed. Way exhibited this arc on the mast of a yacht off the Isle of Wight and it excited great interest. About the same time Gladstone also produced it and examined its spectrum (J. H. Gladstone, "On the Electric Light of Mercury," Phil. Mag., (4) 20, pp. 249-253, 1860). Since then a number of different designs have been proposed, including an inverted U-tube with the ends dipping in mercury and the arc passing in the Torricellian vacuum.

The first practical lamps have been made by Arons (L. Arons, "Uber einen Quecksilberlichtbogen," Wied. Ann., 47, pp. 767-771, 1892; "Uber den Lichtbogen zwischen Quecksilberelectroden, Amalgamen und Legirungen," Wied.

Ann., 58, pp. 73-95, 1896) and by Cooper Hewitt (*loc. cit.*). Fig. 12 shows the form of the Arons lamp most used in laboratories. At the electrodes further mercury reservoirs are attached outside to prevent the temperature rising too high. The arc is struck by inclining the lamp and letting a drop run from A to B. Only weak currents can be used, otherwise the lamp becomes too hot. For laboratory purposes it is therefore often put in a water bath. This causes the vapour to condense on the side of the bulb tube and the light is then obscured. To obviate this, the design has been altered by several experimenters and a tube with a plane window on its end has been attached to the upper part of the U. The window projects out of the water bath and is warmer; consequently no vapour condenses on it. It is the light from the window that is used.

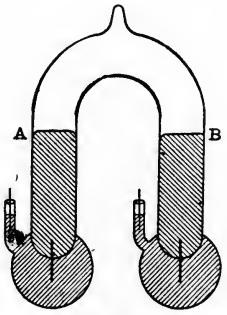


FIG. 12.—DIAGRAM OF ARONS' LAMP.

The brightness, of course, depends on the current, P.D., temperature and diameter of the tube. All these factors have been exhaustively studied by Cooper Hewitt. The current he uses is of the order 3·5 amperes, and the temperature of the vapour about 145°C. He adds an induction and a resistance to his lamps to steady them.

A determination has been made of the radiant efficiency of an Arons lamp by Geer (Wm. C. Geer, "The Radiant Efficiency of the Mercury Arc," Phys. Rev., 16, p. 94, 1903). The E.M.F. between the terminals of the lamp was 14 volts, and the current ranged from 5 to 9 amperes. The result varied between the very high values of 41 per cent. and 48 per cent. Two facts

must, however, be set against this high result. First of all, the method used was the water and iodine filter method employed by Merritt in his work on the carbon glow lamp, and it gives values too large. Again, the result is only for the radiation from the vapour, the radiation from the hot glass being eliminated by measuring the radiation from the lamp, after it was extinguished, at regular intervals of time, plotting a cooling curve and producing this curve backwards to the time of extinguishing the lamp. The ordinate for this time gave the part of the original effect that was due to the hot glass and by subtraction the part due to the incandescent vapour could be found. One cooling curve is given in the paper, and according to it the hot-glass radiation is three times as great as the mercury vapour radiation. The convection loss from the mercury arc must be large; but even allowing for it, if the radiant efficiency is 48 per cent. we should get more than two candles per watt from it owing to the green colour of the light.

Owing to the nature of the spectrum—namely, to the fact that it consists of sharp lines too narrow for our measuring instruments—a satisfactory energy curve cannot be taken. The infra-red spectrum has been explored by W. W. Coblentz and W. C. Geer ("The Infra-red Emission Spectrum of the Mercury Arc," Phys. Rev., 16, p. 279, 1903), who used a radiometer, and the intensity of the lines from a quartz lamp has been studied by A. Pflüger ("Die Gesetze der Temperaturstrahlung und die Intensitätsverteilung im Spektrum der Quecksilberlampe," Ann. d. Phys., (4) 26, pp. 789-805, 1908) and E. Ladenburg ("Uber die spektrale Energieverteilung der Quecksilberlampe aus Quarzglas," Phys. Zs., 5, pp. 525-528). A spectro-photometric examination of the spectrum has been made by P. Vaillant ("Sur les variations avec la temperature des spectres d'emission de quelques lampes electriques," Comptes Rendus, 142, pp. 81-83, 1906).

The great disadvantage of the mercury lamp, as has been said, is its colour, which gives everything a ghastly appearance, and being practically monochromatic is no use for the discrimination of colour. Cooper Hewitt endeavoured to correct the colour by enveloping the lamp in a silk impregnated with a fluorescing substance. The loss of intensity is then said to be

25 per cent. Attempts have also been made to correct it by using the mercury lamp together with glow lamps or other lamps of a pronounced reddish tint. In a recent article ("White Light from the Mercury Arc and its Complementary," Bull. Bureau of Standards, 6, p. 265, 1909), H. E. Ives discusses the best light to use with the mercury arc for the purpose of correcting its colour, and finds the tungsten glow lamp or Welsbach mantle to be most suitable. To 1 c.p. of mercury arc should be added 0·54 c.p. of tungsten glow lamp. The efficiency of the combination should then be 0·80 watt per candle. Most attempts to improve the colour have, however, been made by adding substances to the mercury, potassium amalgams, for example, or zinc. In the article cited above, Leblanc says it has been found that the colour cannot be corrected in this way, the arc passing in one or the other of the substances employed, but never in a mixture of both.

Heræus ("The Kuch Mercury Lamp," O. Bussmann, Elektrot. Zs., 38, 1907, also the Illuminating Engineer, 1, p. 81, 1908) states that the amalgam method fails because generally the added metal tends to gradually separate out at one pole. He also tried the effect of rendering refractory substances, such as Nernst substances and metallic oxides, incandescent, by making use of the high temperature of the arc, but without satisfactory practical results, and states that the addition of other substances has an injurious effect on the life of the lamp. Other experimenters also describe on the effect of introducing amalgams (E. Gehrcke und O. von Baeyer, Elektrot. Zs., 27, pp. 383–384, 1904; Leo Arons, "Eine Amalgamlampe mit reichem Linienspektrum," Ann. d. Phys. (4) 23, pp. 176–178).

Lately the Brush Company have introduced a new mercury lamp called the "Quartzlite" (The Electrician, Vol. LXVI., p. 512, 1911). The tube is made of quartz, and owing to quartz being able to withstand a much higher temperature than glass, a greater current density and consequently a higher temperature can be used, and this gives a much whiter light besides increasing the radiant efficiency. The pressure inside the lamp is very great; this broadens the lines and gives a continuous background to the mercury spectrum. Red rays

are also obtained by the use of a platinum or tantalum stud as one of the electrodes. The makers claim to obtain over two candles per watt with a lamp rated at 3 to 3·5 amperes at 250 volts.

Quartz tubes, of course, transmit ultra-violet radiation injurious to the eyes, and in general use must be surrounded with a glass globe. These ultra-violet radiations, although injurious to the eyes, are useful for photographic and other purposes.

Most commercial mercury lamps have a magnetic arrangement for tilting them when current is started, and so striking the arc automatically. A novel method for starting the arc has recently been patented by J. S. Anderson and G. B. Burnside. They have a heating coil in series with the lamp, in a recess in the tube near one electrode. Owing to the form of the tube this coil vaporises some mercury, and so breaks the column.

Before leaving the mercury arc it should be stated that it is claimed for the green colour that it is soothing. A curious instance, about which one would like to hear more, is cited in support of this in the article by Maurice Leblanc (*loc. cit.*). He states that in a certain department in Messrs. Lumière's factory, at Lyons, red lights were employed. They had a bad psychological effect; the staff was "ingouvernable." Green light was then substituted with the best results.

CHAPTER X.

THE LIGHT OF THE FUTURE.

We have considered all the principal means of producing artificial light, and have seen that the radiant efficiency probably in no case exceeds 10 per cent. and that the luminous efficiency in the most favourable case probably does not exceed 5 per cent. That is, our lamps do not succeed in transforming more than one-twentieth of the energy supplied to them into light. As energy transformers they are very poor, and their inefficiency in this respect has been commented on on all sides.

If we consider the data of the preceding chapters, we see that what progress has been made has been in three directions; first, in the direction of higher temperatures; second, in using substances with selective emission; and, third, by employing luminescence as well as temperature radiation. Flames, the carbon glow lamp and the pure carbon arc, are, speaking generally, all cases of the pure temperature radiation of solid carbon, their relative efficiency being due solely to the difference of temperature. Carbon is approximately a black body. The superiority of the metal filament lamp over the carbon glow lamp is due partly to its higher temperature and partly to the shape of its energy curve. All metals have a region of strong reflection in the infra-red, and this diminishes their emission in these wave-lengths. The efficiency of the Welsbach mantle is due, on the other hand, to its selective emission; the energy curve has two chief maxima, and one of them falls near the visible spectrum.

Further progress could, therefore, be made by pushing the temperature still higher and by looking for substances with more favourable selective emission. But, as the temperature

of the arc is the melting point of carbon, it is doubtful if we can get higher temperatures than those in use at present. The fact that there are higher temperatures in the sun is no reason that we can get them here. It is difficult to say how far progress can be made by finding substances with a more favourable selective emission. Auer von Welsbach, it is well known, tried different substances before choosing the ceria-thoria mixture, and there is little doubt that the scientists connected with the manufacture of the Welsbach mantles and Nernst filaments will have information on this point not accessible to the general public. Two facts can, however, be stated about selective emission. The substances which show it in a most marked degree are the oxides of the rare earths. If a combination of the rarer of these is found suitable there will always be the expense and labour of purifying them, which is an extremely lengthy process. Again, all substances showing selective emission tend to radiate like the black body on being raised to high temperatures—witness the Nernst glower.

Leaving temperature radiation and turning our attention to sources in which there is luminescence, we find two in the number we have considered—namely, the chemical arc and the mercury arc. From both of these there is still, however, a considerable amount of temperature radiation, and temperature radiation apparently always means waste dark heat. The ideal which the illuminating engineer has before him is cold light, light without heat, a source which fulfils the definition of the perfect artificial illuminant set up in the first of these studies, having an energy curve similar to the energy curve of average daylight, but stopping abruptly at both ends of the visible spectrum. This would be cold light, as the source would radiate no other energy but that absolutely necessary for the light production.

Now, how is this cold light to be obtained? In popular lectures on this subject it is usual at this point for the lecturer to refer to the vacuum tube and to fluorescence as supplying indications of the directions in which progress is eventually to be made. This statement is, of course, useful from the point of view of the lecturer, as it supplies an occasion for a picturesque display of vacuum-tube pyrotechnics and for a

reference to the firefly as the cheapest source of light. What grounds are there for the truth of the statement ?

Let us first of all take the case of the vacuum tube. As the readers of this chapter are doubtless aware, it has been developed as a commercial illuminant by Mr. D. McFarlan Moore. But before describing his method, we shall take some of the older results. Formerly, the vacuum tube was thought to have a very high temperature. More recent papers, in particular those of E. Warburg (" Uber Wärmeleitung und Temperatur der in Geisslerschen Röhren leuchtenden Gase," Wied. Ann., 54, p. 265, 1895) and R. W. Wood (" Experimentelle Bestimmung der Temperatur in Geisslerschen Röhren," Wied. Ann., 59, pp. 238-251, 1896), have shown that the temperature is, on the contrary, very low. On the assumption that all the electric energy consumed reappeared as heat, Warburg calculated that in a certain hydrogen tube the temperature at no point could exceed 133°C. Wood placed a bolometer consisting of a 2 cm. long spiral of platinum-iridium wire inside a nitrogen tube and read the temperature when the current and pressure were varied. The current was direct current from a battery of 600 accumulators giving 1,250 volts. The bolometer was also moved along the tube and the temperature read at different points. In carrying out this part of the investigation the Geissler tube was formed from the Torricellian vacuum of a barometer and the bolometer entered through the mercury column. Wood's results showed a temperature inside the tube of the order of 30°C. to 40°C. Therefore, in one sense at least, light from the vacuum tube is cold light.

The efficiency of vacuum tube radiation has been studied by G. Staub (Inaug. diss. Zurich, 1890), K. Ångström (" Bolometrische Untersuchungen uber die Stärke der Strahlung verdünnter Gase unter dem Einflusse der electrischen Entladung," Ann. d. Phys., 48, p. 493, 1893) and E. R. Drew (" The Luminous Efficiency of Vacuum Tube Radiation," Phys. Rev., 17, p. 321, 1903). Staub placed the tube in a transparent ice calorimeter, and noted the heat given out when two or three Leyden jars were discharged through it. The tube was then covered with opaque varnish, and the experiment repeated. In this case the total energy given out was

measured. The result showed that 20 to 30 per cent. of the energy escaped when the tube was transparent.

Ångström's investigation is more important for our purpose, and so it must be described at more length. Four gases were experimented on—oxygen, hydrogen, nitrogen and carbon dioxide.

The vacuum tubes were used both with an induction coil and a battery of 800 accumulators. The P.D. and the current in the vacuum tube were measured respectively with a quadrant electrometer and a highly insulated dead beat galvanometer. The vacuum tube had rock-salt windows. The radiation was measured by a bolometer, and was standardised by means of Ångström's pyrheliometer, so that the readings could be interpreted in cals./cm^2 seconds. The investigations showed that as long as the pressure was constant, the radiation was proportional to the current, except for high currents when the gases underwent permanent changes. Also, as long as the pressure was constant, the distribution of the energy throughout the spectrum was independent of the current. The variation of the radiant efficiency with the pressure was therefore studied, the bolometer reading being taken when the free radiation of the gas was measured and when the radiation was measured through a plate of alum 3·95 mm. thick. The radiation from the walls of the tube was eliminated by taking a cooling curve, in somewhat the same way as was afterwards followed by Geer. The behaviour of the four gases was widely different, and the total radiation stood in no apparent relation to the absorption of the gas at ordinary temperatures. For small P.D. the radiant efficiency was found in some cases to be very large. For example, for nitrogen it had a value about 90 per cent.; the luminous efficiency had, however, a value of about only 8 per cent.

Drew in his investigations employed a radiometer and a vacuum tube with fluorite windows. He used a 1 cm. water cell to absorb the dark heat, and air was the only gas experimented on. The value found for the radiant efficiency at a pressure of 1 mm. was approximately 20 per cent. An energy curve of a tube taken with rock-salt prism and radiometer is also given in his paper.

The Moore vacuum tube has been described in a paper by the inventor to the American Institute of Electrical Engineers, an abstract of which is given by THE ELECTRICIAN (Vol. LIX., p. 342). There is also an article by Prof. J. A. Fleming (Illuminating Engineer, Vol. I., p. 19) giving photographs of several installations, including the well-known one at the Savoy Hotel, London, and also describing a test of the efficiency of the latter. Finally, there is an account of some tests made on it by Prof. Wedding at Charlottenburg (THE ELECTRICIAN, Vol. LXV., p. 763).

When a vacuum tube has been run some time it becomes "hard"—that is, the vacuum becomes higher. The gas seems to be absorbed. This is a well-known fact in connection with Röntgen bulbs. Mr. D. McFarlan Moore, who had in 1907 been experimenting 12 years with his tubes, has tried four methods of replenishing the gas. In the method finally adopted there is a side tube closed by a porous carbon plug, which is covered with mercury when a plunger is lowered. When the plug is uncovered gas diffuses into the tube through the carbon; when the plug is covered no gas can enter. If the pressure in the tube diminishes its conductivity increases. Consequently, the current increases and the increase in the current actuates the plunger. The degree of vacuum required is 0·10 mm. This automatic feeding arrangement keeps the pressure constant to 0·01 mm.

The tubes vary in length from about 40 ft. to 220 ft., and are about 2 in. in diameter. The ends are equipped with graphite electrodes, are brought together and connected to the high-tension terminals of a small transformer, which, together with the terminals and the feeder valve described above, is contained in a small iron box. There are thus no exposed high-tension currents. The voltage employed varies from 10,000 to 12,000 volts, depending on the length of the tube. The current is about 0·3 ampere.

A great advantage of the Moore tube is the small intrinsic brightness (0·2 hefner per square centimetre), which enables it to be used without any arrangement for diffusing the light. Also, owing to the length of tube employed, we have a shadowless illumination. If carbon dioxide be the gas employed,

the colour is said to be nearer sunlight, and hence more suitable for colour discrimination than any other artificial illuminant.

Prof. Fleming found that the tube installed at the Savoy required 1·78 watts per candle; Prof. Wedding, in his tests, finds 1·53 watts per candle. These figures include the losses in the transformer. Prof. Wedding in his tests replaced the Moore tube by 42 tantalum lamps, which consumed exactly the same power, and found that the average illumination was about the same in each case.

The nature of the gas in the tube is important. According to Mr. Moore, nitrogen gives 20 times as much light as hydrogen and twice as much light as carbon dioxide for the same expenditure of energy.

According to a recent paper by M. Georges Claude (Comptes Rendus, 151, p. 1122, 1910; *see* note "Athenæum," January 14, 1911), neon is more suitable than nitrogen. Finding himself with large quantities of neon at his disposal, as a by-product from the commercial manufacture of liquid air, he has worked out a system of artificial lighting by its means. Using tubes 6 metres long and 4·5 cm. in diameter, he obtains 0·80 watt per candle, and expects to reduce this to 0·50 watt per candle by using longer tubes. These figures include the losses in the transformer. Neon is remarkable for its small dielectric resistance. The voltage used with the above tubes was 1,000 volts; if nitrogen is employed instead of neon, 3,000 volts are required.

In view of the results obtained by Moore and Claude, the vacuum tube must be said to promise exceedingly well. The efficiency in watts per candle hitherto attained, it is true, is not better than that given by some other sources, but the whole method is yet in its infancy, and there is room for a vast amount of experimenting. We have no data on the energy spectra of vacuum-tube radiation beyond what is cited in this chapter, but the vacuum-tube is not like temperature radiation; there is no *a priori* reason why the maximum of its radiation should lie in the infra-red; and there surely must be some gas, or mixture of gases, which gives a maximum of radiation in the visible spectrum under some conditions of pressure and

temperature and current density. As far as we are aware, only three or four gases have been tried yet, and their possibilities have been by no means exhausted.

One point deserves mention. Once the dielectric resistance is broken down, a high voltage is not necessary, and the vacuum tube may work with a low voltage and large current, provided it does not crack. There is no sharp distinction between the arc and the vacuum tube. But by analogy with the arc, with low voltages, there must be high temperatures, and consequently large conduction and convection losses.

Before leaving the subject of vacuum tubes, it ought to be mentioned that Hönig (Martin Hönig, "Optischer Nutzeffekt electrodenloser Vacuumröhren," Inaug. diss. Rostock, 1901), in a paper to which I have been unable to get access, is cited as obtaining 2·21 watts per candle with an electrodeless mercury vacuum tube. Also H. Ebert states ("Die ökonomischsten Lichtquellen," Eder's Jahrb. f. Photogr., 9, pp. 47–49, 1895; also "Uber lang andauernde electrische Schwingungen und ihre Wirkungen," Ann. d. Phys., 53, p. 144, 1894) that he has obtained $\frac{1}{40}$ candle from about 10^{-6} watts, the light being produced by exposing the vacuum tube to very slowly damped Hertzian waves. This is equal to 25,000 candles per watt! Full details are not given as to how the watts were calculated. The difficulties of obtaining the energy consumed are certainly very great in the case in question. No faith can be placed in the result.

Let us now turn our attention to fluorescence. This has been mentioned by different people as a property of matter which may ultimately be put to practical use for illumination. H. G. Wells, with that skill of his with which he seizes on a tendency or idea of modern civilisation and lets us see it is his novels crystallised into a fact in the future, has dealt also with artificial illumination. In "The First Men on the Moon" the inhabitants of the moon illuminate their caverns by fluorescence. A fluorescent fluid was made by machinery and dripped luminously into a tank of light. It was a cold blue light, a sort of phosphorescent glow, but infinitely brighter, and from the tanks into which it fell it ran in conduits athwart the cavern. When it splashed on the feet of the two earth-men

it felt quite cold and made their feet luminous for a long time afterwards.

This is no doubt very inspiring. Let us see what there is to warrant it.

If when light is incident on a substance it causes it to emit light of a wave-length different from, and not necessarily longer than, the wave-length of the incident light, the substance is said to be fluorescent. If the light from the substance persists for a short time after the incident light is cut off, the substance is said to be phosphorescent. Phosphorescence in this sense is quite different from the glow emitted by phosphorus, which is due to slow chemical action. During fluorescence and

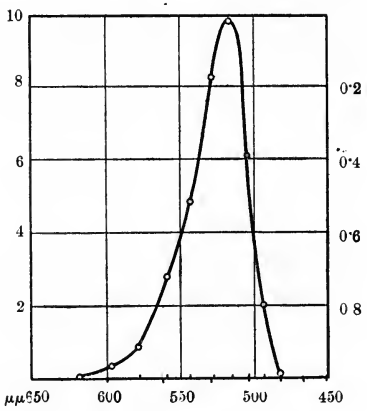


FIG. 13.

phosphorescence the chemical state of the substance does not change. Examples of fluorescent substances are solutions of sulphate of quinine, chlorophyl and fluorescein. The difficulty in observing fluorescent light lies in obtaining it pure and unmixed with the exciting light, as the latter is usually much stronger. If the fluorescence emitted by any substance is compared with the light from a glow lamp by means of a spectrophotometer it is found to have a well-defined maximum, usually falling away to zero on each side at points within the visible spectrum. The curve in Fig. 13, which is for a piece of uranium glass, has been obtained in this way (R. A. Houstoun,

"A Negative Attempt to detect Fluorescence Absorption," Proc. Roy. Soc., Edin., 29, p. 401, 1909). Fluorescent spectra are much too weak to measure with a thermopile or radiometer, but if the energy curve of the comparison source is taken the energy curve of the fluorescence may be obtained. Energy curves for fluorescein in water, and eosin and resorufin in alcohol, have recently been taken in this way by E. L. Nichols and E. Merritt, the comparison source being an acetylene flame ("Studies in Luminescence, XI. The Distribution of Energy in Fluorescence Spectra," Phys. Rev., 30, p. 328, 1910).

Now, according to these energy curves, the energy of fluorescence lies within the visible spectrum and in some cases in its most luminous region. Before jumping to the conclusion, however, that we have here the end of our quest, there are one or two facts to be considered. We do not know that there is no energy radiated in the infra-red. There is only one research bearing on this subject, the well-known investigation of Langley and Very ("On the Cheapest Form of Light, from Studies at the Allegheny Observatory," Amer. Journ. of Sc., (3) 40, p. 97, 1890) on the light of the Cuban firefly, the Pyrophorus Noctilucus. The insect's light was examined spectrophotometrically, and the following table gives its brightness for different wave-lengths when compared with an Argand flame:—

Wave-length .....μ	0·49	0·51	0·53	0·54	0·56	0·58	0·59	0·60
Brightness	0·02	0·21	0·34	0·37	0·24	0·19	0·17	0·09

It has thus a well-defined maximum in the middle of the spectrum.

An attempt was then made with a very sensitive bolometer to measure the heat which the insect radiated in the infra-red. A glass plate was used to cut out the animal heat that would be radiated, whether the insect was luminous or not. The effect observed then was very much less than the effect produced by other light sources of equal area and equal brightness. Further work was done on the subject in 1902 ("Annals Astrophys. Obs.," 2, p. 5), but no heating could be detected by the bolometer in spite of its very great sensitiveness. Langley concluded from his work that, apart from the heat due to animal processes, the firefly's radiation was all light, and that it was

consequently the cheapest form of light. He drew the conclusion that, what Nature could do on this small scale, man must be eventually capable of doing on a larger scale, and that there was no reason why we should be satisfied with our present inefficient means of producing light.

The energy curve of another firefly, the Photinus Pyralis, has recently been obtained photographically by W. W. Coblentz and H. E. Ives ("Luminous Efficiency of the Firefly," Bull., Bureau of Standards, 6, p. 321, 1910). It also descends to zero on both sides at points well within the visible spectrum, but they made no thermal measurements, so that the work of Langley and Very on the efficiency of the process that is taking place stands alone. Langley's reputation as a physicist is a great one, and there is nothing to take exception to in his paper. His results were negative, however, and the quantities of heat involved extremely small. I think, therefore, that the experiment is worth repeating, especially as Prof. Konen, who contributes the section on phosphorescence and fluorescence to Kayser's "Spectroscopie," states at p. 656, vol. IV., of the latter book that the light of the firefly is probably not due to true phosphorescence, but to a slow chemical change.*

Apart altogether from the firefly, it would be extremely interesting to get a determination of the efficiency of the ordinary process of producing fluorescence in the laboratory—namely, by exposing the fluorescent substance to the ultra-violet radiation from a spark-gap. We wish to know if the fluorescence is so faint merely because the ultra-violet light radiated in *one* direction is emitted by the substance in *all* directions, or whether the energy of the ultra-violet radiation is also consumed in some other way. All fluorescence, both the line fluorescence of vapours and the banded fluorescence of solids and liquids, is extremely faint, but it should be possible to get a rough answer to the question by a combination of photometric and energy measurements. Then it would be easier to pro-

* Since the above was written a paper has been published (H. E. Ives, "Further Studies of the Firefly," Phys. Rev. 31, p. 637, 1910) in which the author points out a deficiency in Langley's method and makes an attempt to detect the infra-red radiation from fireflies by its extinguishing effect on phosphorescence. He concludes that his experiments render Langley's results more probable.

nounce an opinion on the prospects of fluorescence. But in dealing with a subject of this sort one can hardly be too cautious; there is no saying what unexpected direction progress may take. And, from the nature of the field, it is exceedingly likely that the step forward will follow from some investigation undertaken with another purpose altogether.

In any case, if ultra-violet radiation can be transformed efficiently into light, it will be easy to produce the ultra-violet radiation efficiently. Pflüger ("Die Anwendung der Thermosäule im Ultraviolett und die Energieverteilung in den Funkenspektren der Metalle," Ann. d. Phys., (4) 13, p. 890, 1904) has discovered that the maximum emission of energy in the spark spectra of metals takes place far in the ultra-violet. Our photographic plates between 0·200 and 0·300μ have apparently not been so very sensitive. It is only the great quantity of energy in the lines there that has enabled us to obtain photographs at all. The following table is taken from Pflüger's paper. The spark-gap was about 3 mm. long, it was fed from an induction coil with hammer interrupter, and was connected up with one Leyden jar. The infra-red beyond 0·580μ was separated out with a red glass filter and the region 0·280–0·180μ with a Uviol glass filter.

Distribution of the Energy in the Spark Spectra of Metals.

Metal.	Region.		
	Infra-red to 0·580μ	0·580–0·280μ.	0·280–0·180μ.
Aluminium ...	11·4 per cent.	26·6 per cent.	62·0 per cent.
Cadmium.....	9·7 ,,	24·3 ,,	66·0 ,,
Zinc	11·0 ,,	20·8 ,,	68·2 ,,
Iron	3·6 ,,	16·4 ,,	80·0 ,,
Cobalt	5·0 ,,	14·5 ,,	80·5 ,,
Nickel	7·0 ,,	17·7 ,,	75·3 ,,
Silver	15·0 ,,	28·5 ,,	56·5 ,,
Copper	13·1 ,,	21·3 ,,	65·6 ,,
Gold	21·2 ,,	39·3 ,,	39·5 ,,
Tin	18·7 ,,	37·3 ,,	44·0 ,,
Lead.....	26·5 ,,	31·3 ,,	42·2 ,,
Palladium	16·0 ,,	28·0 ,,	56·0 ,,
Iridium	17·1 ,,	27·4 ,,	55·5 ,,
	...	0·580–0·330μ	0·330–0·180μ
Magnesium ...	12·3 per cent.	20·6 per cent.	67·0 per cent.

CHAPTER XI.

ON THE ABSOLUTE MEASUREMENT OF LIGHT: A PROPOSAL FOR AN ULTIMATE LIGHT STANDARD.*

The measurement of the intensity of a source of light is, it is well known, a somewhat unsatisfactory process. The eye cannot estimate light intensity; it can only tell when the illumination of two adjacent surfaces is equal. If, for example, we desire to measure the intensity of a metal filament lamp, we compare it with a Hefner lamp and say that the intensities are inversely as the squares of the distances from the photometer head, when equal illumination is obtained. In strictness, however, this method is applicable only when the colours of the two sources, or more accurately when the distribution of energy in the spectra of the two sources, is exactly the same; for the relative luminosity of the different colours of a spectrum varies with the intensity of that spectrum. Abney has two well-known curves illustrating this.† One, which represents the relative luminosity of the different colours of a spectrum at ordinary intensity, has a maximum in the orange; the other, which is for a spectrum with the same distribution of energy, but with an intensity of less than 1/100 candle-foot, has its maximum in the green. If, therefore, we have an extremely long photometer bench, and an experimenter with normal colour vision compares the intensities of the metal filament lamp and the Hefner lamp, at first placing the Hefner lamp 1 ft. from the photometer head and afterwards placing it more than

* This chapter appeared at first in the Proc. Roy. Soc., A. 85, p. 275, but after it was printed P. G. Nutting published a recalculation of König's data, which necessitates alterations in the original paper. These alterations, as well as a few amplifications, have been made here.

† "Colour Vision," p. 103.

100 ft. from the latter, he should not obtain the same result both times. In the first case, owing to the reddish tint of the Hefner lamp, the intensity of the metal filament lamp should appear less. If, again, a second observer, whose colour vision is slightly abnormal, compares the lamps at the first distance, he gets a third result.

Of course, the difficulty does not arise in practice, because the sources to be compared have usually the same colour and the illumination of the field of the photometer does not vary over a wide range. Still, a standard unit of light should meet all conceivable cases, and we are at present unable to state satisfactorily in terms of our standards, once for all, the candle-power of, for example, a mercury vapour lamp. In order to be definite we must specify, first of all, normal colour vision on the part of the observer, and then we must state the illumination of the fields he compares. It is, of course, the Purkinje effect, the change from rod to cone vision, that causes all this trouble. And it is precisely within the range of illumination in common use, 1 to 100 metre-candles, that this change from rod to cone vision takes place.

I think it is now possible to place the photometry of different coloured lights on an exact footing, at least as far as ultimate measurements are concerned, by removing it out of the field of physiology altogether into the field of electricity, which is a much more exact science.

Why can we not measure candle-power by means of a thermopile? Simply because the thermopile measures the total energy radiated, irrespective of wave-length. The energy of every radiation receives the same value. Now, infra-red and ultra-violet radiations produce no effect at all on the eye, and the light-producing effect of the same quantity of energy is much greater in the middle of the spectrum than at its ends. If we place in front of the thermopile a light filter which has the property of stopping entirely all the infra-red and ultra-violet radiation and of cutting down the energy of the visible spectrum in inverse ratio to its light-producing effect, that is, *if we weight each radiation according to its visibility*, then the deflections will be proportional to the light received. This combination of filter and thermopile is then a kind of electric eye, which

has a property that the human eye has not, namely, the property of registering the intensity of the light to which it is exposed.*

The relative visibility of light of different wave-lengths for different intensities of that light has as yet been determined only for one eye, namely, that of Prof. A. König, and the results are given in the following very convenient table, which we borrow from a paper by P. G. Nutting.† The second horizontal row gives the illumination in metre-candles :—

—	T	A	B	C	D	E	F	G	H
	0·00024	0·00225	0·0360	0·575	2·30	9·22	36·9	147·6	590·4
0·430μ	0·031	0·093	0·127	0·128	0·114	0·114	...	...	...
0·450	0·33	0·30	0·29	0·31	0·23	0·175	0·16	...	...
0·470	0·63	0·59	0·54	0·58	0·51	0·29	0·26	0·23	...
0·490	0·96	0·89	0·76	0·89	0·83	0·50	0·45	0·38	0·35
0·505	1·00	1·00	1·00	1·00	0·99	0·76	0·66	0·61	0·54
0·520	0·88	0·86	0·86	0·94	0·99	0·85	0·85	0·85	0·82
0·535	0·61	0·62	0·63	0·72	0·91	0·93	0·98	0·99	0·98
0·555	0·26	0·30	0·34	0·41	0·62	0·84	0·93	0·97	0·98
0·575	0·074	0·102	0·122	0·168	0·39	0·63	0·76	0·82	0·84
0·590	0·025	0·034	0·054	0·091	0·27	0·49	0·61	0·68	0·69
0·605	0·008	0·012	0·024	0·056	0·173	0·35	0·45	0·54	0·55
0·625	0·004	0·004	0·011	0·027	0·098	0·20	0·27	0·35	0·35
0·650	0·000	0·000	0·003	0·007	0·025	0·060	0·085	0·122	0·133
0·670	0·000	0·000	0·001	0·002	0·007	0·017	0·025	0·030	0·030
λ max.	0·503	0·504	0·504	0·508	0·513	0·530	0·541	0·543	0·544

Prof. König's colour vision was normal, and so in default of other data we can take this table as applying to the average

* After writing this chapter my attention was called to the fact that an attempt to put this method into practice has already been made by Ch. Féry (" Photométrie à lecture directe : Rendement optique de quelques luminaires," Jour. de Phys., 4, p. 638, 1908). He used a solution of copper acetate in water with a radiomicrometer, and has selected the same total thickness of water as myself, namely, 4 cm. He has not, however, gone into the matter fully, and does not give the fraction transmitted by his filter throughout any part of the spectrum. Copper acetate alone cannot give the proper absorption in the violet. I have also used a radiomicrometer, and my experience is that it is inferior in sensitiveness to the apparatus described in this chapter, although possessing the advantages of simplicity and cheapness.

† " The Visibility of Radiation : A Recalculation of König's Data." Bull., Bureau of Standards, 7, p. 238, 1911,

human eye. As an illustration of the use of the table we see from column D, that if an illumination of 2·30 metre-candles is to be produced in succession by light of wave-length 450 and 535$\mu\mu$, the energy required in the two cases must be as 91 to 23.

In choosing a filter we must fix on something capable of accurate reproduction. This rules coloured glasses out of the question, unless they are made under standard conditions. We are therefore restricted to liquids in glass cells. Commercial dyes of ill-defined composition are subject to the same objection as coloured glasses. Solutions of salts which can be varied in strength give us more latitude, and are therefore to be preferred to liquids of a fixed composition. A series of researches on the absorption of light by aqueous solutions of inorganic salts in the ultra-violet, visible spectrum, and infra-red is now being carried out in the physical laboratory of the University of Glasgow, as a result of which I am in possession of a considerable amount of data not at present accessible to others, and from it I have no hesitation in concluding that the most suitable filter is a 3 cm. thickness of copper sulphate in water, of concentration 0·200 gramme-molecule per litre, followed by a 1 cm. thickness of potassium bichromate of concentration 0·0025 gramme-molecule per litre. I have examined eight different kinds of commercial coloured glass, but none of them is of the least use for the purpose, owing to not stopping the near infra-red.

The absorption of light in aqueous solutions of inorganic salts obeys the following equation :—

$$I = I_0 \cdot 10^{-Ac},$$

which also defines A, the molecular extinction coefficient of the salt for the wave-length considered. I_0 is the initial intensity of the light, I its intensity after passing through a thickness d of solution, d being measured in centimetres, and c is the concentration of the solution in gramme-molecules per litre. We may take A as independent of c except for wide ranges and at particular points in some spectra.

The following tables give the values of A for the two salts in question. The values for the visible spectrum are taken from

VISIBLE SPECTRUM. GRÜNBAUM'S RESULTS.

λ.	A.			λ.	A.
	$CuSO_4 5H_2O$ $c=0{\cdot}6159.$	$K_2Cr_2O_7.$ $c=0{\cdot}003399.$	$K_2Cr_2O_7.$ $c=0{\cdot}0J3399.$		$CuSO_4 5H_2O$ $c=0{\cdot}6159.$
0·4800μ	0·0098	...	216·0	0·5780μ	3·472
0·4917	0·0166	...	136·0	0·5893	0·652
0·5003	0·0232	...	92·1	0·6004	0·890
0·5086	0·0358	62·4	58·0	0·6103	1·160
0·5209	0·0630	28·7	26·2	0·6239	1·610
0·536	0·1055	7·24	6·2	0·6362	2·08
0·5461	0·168	3·44	...	0·6452	2·456
0·5608	0·273	...	...	0·6563	3·295

VISIBLE SPECTRUM. RESULTS OBTAINED BY A. S. RUSSELL AND THE AUTHOR.

$CuSO_4 5H_2O$.			$K_2Cr_2O_7$.		
c.	λ.	A.	*c.*	λ.	A.
0·2263	0·450μ	0·026		0·463μ	394·4
...	0·537	0·122		0·471	322·6
...	0·572	0·399		0·480	251·9
...	0·590	0·672	0·00157	0·489	179·1
...	0·598	0·883		0·499	119·3
				0·510	65·69
				0·521	23·47
				0·529	12·75
				0·537	7·06
				0·544	3·69
...	...	...	0·0392	0·552	2·11
				0·568	1·10
				0·588	0·68
				0·633	0·46
				0·697	0·14

INFRA-RED.

λ.	A. $CuSO_4$, $5H_2O$. $c=0{\cdot}03435.$	λ.	A. $CuSO_4$, $5H_2O$. $c=0{\cdot}03435.$
0·684	6·36	0·910	9·1
0·720	9·8	0·980	7·1
0·750	11·5	1·07	5·8
0·794	11·7	1·17	4·1
0·850	11·1	1·27	3·0

ULTRA-VIOLET.

$CuSO_4$, $5H_2O$.			$K_2Cr_2O_7$.		
c.	λ.	A.	c.	λ.	A.
0·01	0·267μ	52·0	0·0001	0·241μ	7,160
0·03	0·278	34·0	...	0·269	11,100
0·05	0·282	20·2	...	0·284	7,440
...	0·287	13·0	...	0·291	5,070
0·10	0·291	10·1	...	0·300	2,720
...	0·292	8·6	0·0005	0·308	2,320
...	0·296	6·5	0·0003	? 0·316	2,080
0·30	0·299	3·37	0·0005	0·325	2,320
...	0·309	1·48	0·0001	0·331	2,720
...	0·313	0·78	...	0·336	5,070
...	? 0·322	0·08	...	0·349	7,440
			...	? 0·375	10,000
			...	0·397	7,440
			0·0003	0·410	3,080
			0·001	0·416	1,030

papers by Grünbaum* and by A. S. Russell and the author.† The values for copper sulphate in the infra-red were obtained with a linear thermopile, the source of light being a Nernst glower. The values for the ultra-violet were obtained by means of a quartz photometer of original design which has recently been worked out by John S. Anderson and the author, and a full description of which has already been published.‡ It is, of course, impossible to give values farther into the infra-red owing to the absorption of water. At the strength and thickness used in the filter potassium bichromate does not exercise any appreciable absorption in the infra-red.

The values of A*cd* for the two filters have been calculated from the tables and are shown in the diagram (Fig. 14). The values for copper sulphate are shown by ○'s and the values for potassium bichromate by ×'s; Grünbaum's values are taken for the copper sulphate and our own for the potassium bichromate. The smooth curve is the sum of the ordinates for each salt. The logarithms of the column E in Nutting's table were then calculated, their sign was changed, and they were plotted on the diagram as the dotted curve. In order to facili-

* Ann. d. Phys. (4), 1903, 12, p. 1004.

† Roy. Soc. Edin. Proc., 1908-9, 29, p. 69.

‡ Roy. Soc. Edin. Proc., 1910-11, 31, p. 547.

tate comparison with the smooth curve, the vertical scale for the dotted curve is displaced 0·08 up. Of course, we can add any constant quantity to the ordinates of the smooth curve without altering the relative absorption of the different colours.

The smooth curve agrees with E. The latter gives the relative visibility for an illumination of 9·22 metre-candles. We are therefore justified in assuming that our filters weigh the radiation of the visible spectrum correctly according to its visibility to normal colour vision, the illumination of the field

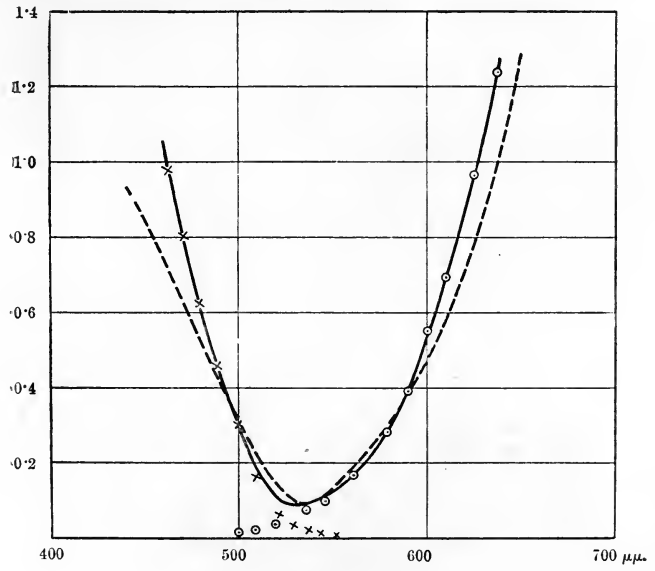


FIG. 14.

being about 9·22 metre-candles. If we take as our standard another illumination of the field, it is easy to shift the minimum of the curve by diminishing the concentration of the copper sulphate and increasing the concentration of the potassium bichromate, or vice versa. The strength of the copper sulphate, however, cannot be weakened much unless an additional thickness of water or of, say, ferrous ammonium sulphate is used, otherwise there will not be a sufficient margin of safety in the infra-red. Aqueous solutions of ferrous ammonium sulphate

are, it is now known, very effective in stopping heat rays while allowing the light rays to pass.* They are much more efficient than alum, which in this respect is no better than water.†

If we neglect the light absorbed in the glass, the fraction of light transmitted by our filter is equal to

$$10^{-0\cdot6A_C} \times 10^{-0\cdot0025A_K} \times k,$$

where A is the molecular extinction coefficient of the copper sulphate, A_K is the molecular extinction coefficient of the potassium bichromate, and k the fraction that would be transmitted by 4 cm. of pure water alone. In order that the effect due to the different constituents of the filter may be seen, I have calculated $10^{-0\cdot6A_C}$, $10^{-0\cdot0025A_K}$, and k throughout the spectrum, using for k the values of E. Aschkinass.‡ The results are given in the second, third and fourth columns of the table on the next page.

The product of the three factors—that is, the transmissivity of the whole filter—is given in the fifth column.

Of course, in addition to the above, the absorption of the glass of the cells has to be considered. Glass absorbs all radiations below $0\cdot330\mu$ and above $3\cdot00\mu$.

The filter is weakest in the infra-red at $1\cdot27\mu$. In the normal energy spectra of our ordinary light sources the ordinates at $1\cdot27\mu$ are about 20 times or thereabouts the ordinates at $0\cdot5\mu$. With the strength used, the stopping power of the filter is hence ample, but this point in the spectrum must be watched if the concentration of the copper sulphate is diminished much.

Having found by calculation that the radiation received by a thermopile through this filter should be proportional to the light incident on the filter, I proceeded by direct experiment to

* R. A. Houstoun and J. Logie, Phys. Zs., Vol. XI., p. 672.

† The agreement might be made better by altering the strengths of the solution slightly, as these strengths were chosen before Nutting's table was recalculated. But as the Physical Society of Glasgow University is at present accumulating data for a great number of observers, similar to that given in Nutting's table, with the purpose of determining the properties of the average eye, it seems better to do nothing further until its results appear.

‡ Wied. Ann., 1895, Vol. 55., p. 401.

λ.	$10^{-0\cdot6A_C}$.	$10^{-0\cdot0025A_K}$.	k.	$10^{-0\cdot6A_C} \times 10^{-0\cdot0025A_K} \times k$
$0\cdot227\mu$ }	$<6\cdot31\ 10^{-11}$	$<1\cdot3\ 10^{-18}$	$0\cdot99$ }	$<8\ 10^{-29}$
$0\cdot241$ }		$1\cdot3\ 10^{-18}$	$0\cdot99$ }	
$0\cdot284$	$6\cdot31\ 10^{-11}$	$2\cdot5\ 10^{-19}$	$0\cdot99$	$1\cdot6\ 10^{-29}$
$0\cdot300$	$1\cdot20\ 10^{-2}$	$1\cdot6\ 10^{-7}$	$1\cdot00$	$1\cdot9\ 10^{-9}$
$0\cdot308$	$0\cdot107$	$1\cdot6\ 10^{-6}$	...	$1\cdot7\ 10^{-7}$
$0\cdot325$	$0\cdot89$	$1\cdot6\ 10^{-6}$	...	$1\cdot5\ 10^{-7}$
$0\cdot336$		$1\cdot9\ 10^{-13}$	...	$<1\cdot9\ 10^{-13}$
$0\cdot397$		$2\cdot5\ 10^{-19}$	...	$<2\cdot5\ 10^{-19}$
$0\cdot416$		$2\cdot6\ 10^{-3}$	...	$<2\cdot6\ 10^{-3}$
$0\cdot463$ }	$<0\cdot986$	$0\cdot105$	...	$<0\cdot105$
$0\cdot471$ }		$0\cdot158$	...	$<0\cdot158$
$0\cdot480$	$0\cdot986$	$0\cdot234$	...	$0\cdot229$
$0\cdot489$	$0\cdot977$	$0\cdot355$	...	$0\cdot347$
$0\cdot499$	$0\cdot968$	$0\cdot501$	...	$0\cdot485$
$0\cdot5086$	$0\cdot951$	$0\cdot661$	...	$0\cdot63$
$0\cdot5461$	$0\cdot792$	$0\cdot982$	...	$0\cdot77$
$0\cdot5780$	$0\cdot521$	$1\cdot00$	...	$0\cdot52$
$0\cdot6004$	$0\cdot292$	...	$0\cdot99$	$0\cdot29$
$0\cdot6239$	$0\cdot108$	...	$0\cdot99$	$0\cdot107$
$0\cdot6452$	$0\cdot0336$	...	$0\cdot99$	$0\cdot034$
$0\cdot684$	$1\cdot54\ 10^{-4}$	...	$0\cdot99$	$1\cdot53\ 10^{-4}$
$0\cdot720$	$1\cdot32\ 10^{-6}$	...	$0\cdot95$	$1\cdot25\ 10^{-6}$
$0\cdot750$	$1\cdot26\ 10^{-7}$	...	$0\cdot91$	$1\cdot14\ 10^{-7}$
$0\cdot794$	$9\cdot55\ 10^{-8}$	...	$0\cdot92$	$8\cdot8\ 10^{-8}$
$0\cdot850$	$2\cdot2\ 10^{-7}$	...	$0\cdot86$	$1\cdot9\ 10^{-7}$
$0\cdot910$	$3\cdot5\ 10^{-6}$	...	$0\cdot73$	$2\cdot5\ 10^{-6}$
$0\cdot980$	$5\cdot5\ 10^{-5}$	...	$0\cdot20$	$1\cdot5\ 10^{-5}$
$1\cdot09$	$3\cdot3\ 10^{-}$	...	$0\cdot48$	$1\cdot6\ 10^{-4}$
$1\cdot17$	$3\cdot5\ 10^{-2}$	...	$0\cdot054$	$1\cdot9\ 10^{-4}$
$1\cdot27$	$1\cdot6\ 10^{-2}$	...	$0\cdot0085$	$1\cdot3\ 10^{-4}$
$1\cdot40$			$2\cdot10^{-41}$	$<2\ 10^{-41}$
			Never $>10^{-18}$ all the way to $8\cdot5\mu$.	

determine if this actually was the case. I had three thermopiles at my disposal, a Rubens linear one with iron-constantan couples and two older ones, of different types, but both with antimony-bismuth couples. The Rubens thermopile, as has been mentioned on p. 2 consists of 20 couples on a length of 2 cm., the wires being soldered together with silver beads, which are flattened into discs of 1 mm. diameter. Hence its receiving area is about 0·157 sq. cm. In the case of each of the other two, the receiving area was about 1 sq. in., and the number of couples was greater, yet the Rubens thermopile was as sensi-

tive, even without its reflectors, reached the steady state in a shorter time and had a very much steadier zero. Only the Rubens thermopile was used.

The galvanometer was a Du Bois Rubens ironclad one, of resistance 10 ohms, the property of the Carnegie Trust for the Universities of Scotland. In order to protect it from vibration, it was suspended from a bracket in the wall by three wires each about $1\frac{1}{2}$ metres long, and hung with its three levelling screws clearing the table by about 1 cm. Between the table and levelling screws loose wads of cotton wool were placed for the purpose of damping any vibrations that might arise. The lamp and scale were $1\frac{1}{2}$ metres from the mirror. The resistance of the thermopile was 5 ohms. At the sensitiveness used, the period was 3 seconds, and $\frac{1}{2}$ mm. on the scale indicated a current of 10^{-9} amperes.

It soon became evident that this high sensitiveness was to be fully utilised. When the thermopile was set up at a distance of 33 cm. from a 32 c.p. carbon glow lamp, with the filters in front, the deflection was only 17 half-millimetres. When this lamp is run at its marked voltage, 250 volts, about 2·6 per cent. of its total radiation is light, that is, lies between $0{\cdot}400\mu$ and $0{\cdot}760\mu$, but only a fraction of this 2·6 per cent. gets through the filter. Perhaps altogether about 1/1,000 of the total radiation passes through the filter.

The thermopile was then set up at a distance of 33 cm. from the 32 c.p. carbon glow lamp with the filters in front, the $K_2Cr_2O_7$ filter being next the thermopile. On the other side of the lamp was a photometer bench, at the other end of which there was a 125-volt tantalum lamp that was run off a storage battery. The carbon lamp and the tantalum lamp were compared by a wedge photometer. When this comparison was being made the tantalum lamp was always shunted by a current balance and constant resistance, the latter being chosen so that the open part of the scale of the balance was in use, and from the indications of the balance the voltage on the tantalum lamp could be kept constant to 1/800 by means of a rheostat. At the voltage used the horizontal candle-power of the tantalum lamp, measured by a Hefner lamp, was 7·13 British candles.

Readings were then taken for different voltages alternately

with the thermopile and with the photometer. One set of results is given in the following table and plotted in the following curve (Fig. 15) :—

TEST OF A 32 C.P. GLOW LAMP.

Voltage.	Galvanometer readings.						Photometer readings.				
	Throws.					Mean.	Individual settings.				Candle-power.
207·1	5·5	4·0	4·0	3·0	4·5	4·2	117·5	114·5	112·5	114·5	6·15
222·5	8·0	7·0	6·5	6·7		7·0	96·5	98·5	96·5	98·5	11·2
251·6	18·0	16·0	17·5	18·0		17·4	77·5	76·5	76·5	76·5	24·9
283·7	38·0	38·0	36·5	36·5		37·2	59·5	57·5	59·5	58·5	53·8
304·7	56·5	56·5	60·0	59·8		58·2	48·5	47·5	49·5	49·5	88·1

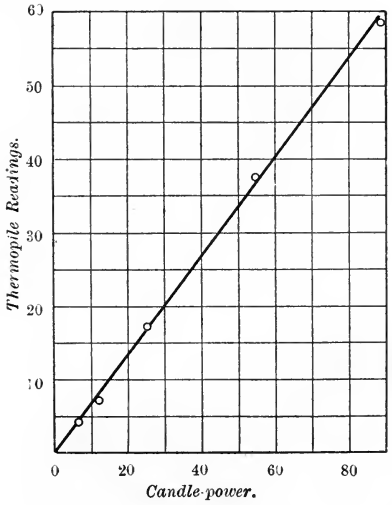


FIG. 15.

Every reading taken is given. At each voltage two readings were first taken with the thermopile, then two settings of the photometer were made; the remaining thermopile readings were then made, and, finally, the last two photometer readings were taken. The numbers given in the table as photometer settings are the distances of the wedge in centimetres from the comparison lamp. The total distance between the two lamps was 220 cm.

The curve should, of course, be a straight line. The agreement is very good when we consider that the galvanometer readings are ½ mm. at 1½ metres distance from the mirror, and that for the last point the photometer was getting rather near the comparison lamp for the inverse square law to hold.

I have altered the strength of the $K_2Cr_2O_7$ to $c=0{\cdot}0125$ and of the $CuSO_4\,5H_2O$ to $c=0{\cdot}350$, and the proportionality still holds.

A thermopile used with such a filter can therefore be employed for measuring candle-power, more especially mean spherical candle-power, because it is only necessary to set up equally sensitive thermopiles over the sphere and to connect them in series with the one galvanometer. All difficulties connected with the integration thus vanish. The method works also quite as well in broad daylight as in a darkened room, the deflections being the same in each case. I think, however, that it is not suitable for commercial application, on account of the high sensitiveness of the galvanometer required. Its importance lies in the fact that it can be used for defining our unit of light and for providing a satisfactory basis on which lights of different colour can be compared, irrespective of intensity and of idiosyncrasy on the part of the observer.

The amount of light lost by reflection at the glass surfaces and by absorption in the glass of the cells can be easily determined by filling the cells with water and using a spectro-photometer to determine the fraction of the incident light transmitted. It is sensibly the same throughout the visible spectrum, and has the value 0·84 for both of the cells employed. It is easy to determine what the galvanometer deflections would have been, had there been no reflection losses or absorption losses in the glass; we have only to multiply by $1/(0{\cdot}84)^2$. In determining the distance of the thermopile from the source of light, we have, of course, to multiply each thickness of glass and liquid traversed by its index of refraction. I propose therefore to define the unit of light intensity as follows:—

The unit of light intensity is that source the total intensity of radiation from which at an optical distance of 1 metre after passing through an ideal filter would be x ergs/cm.^{2} sec., the ideal filter to be one possessing the light-absorbing properties

of a 3 cm. thick aqueous solution of $CuSO_4$, $5H_2O$ of strength 0·200 gramme-molecules per litre and a 1 cm. thick aqueous solution of $K_2Cr_2O_7$ of strength 0·0025 gramme-molecules per litre, but neither to reflect nor to absorb any light in any other way.

I think it better to eliminate the properties of the glass in this way. Different cells have quite an appreciable difference in absorption and the transmission coefficient of a cell is easy to determine. The definition has the advantage of connecting up light closer with the C.G.S. system. By means of his pyrheliometer K. Ångström* has been able to measure the radiation from terrestrial sources to less than 1 per cent., the chief difficulty being to allow for want of "absolute blackness" on the part of the receiving surface. The radiation-receiving surface in my experiments was about 0·157 sq. cm., and the distance from the source 33 cm. By increasing the light-receiving area and using Ångström's method it should be possible to determine x with sufficient accuracy. For the standard candle in the units specified it is roughly 0·8.

* Astrophys. Jour., 1899, Vol. IX, p. 332; Phys. Rev., 1893, Vol. I., p. 365.

CHAPTER XII.

ON APPARATUS AND EXPERIMENTAL METHODS.

It has been seen from the previous chapters that spectrophotometry and the study of energy spectra give valuable information as to the reasons for the performance of a light source. It has been suggested to me that, as these experimental methods are treated very shortly in the laboratory textbooks, some hints on their use might be given here.

The different instruments used for mapping energy spectra have already been mentioned in Chapter I. and reference has been made to the article by W. W. Coblentz comparing their properties. The instrument most suitable in any particular case will, of course, depend to some extent on the resources of the laboratory. If a very sensitive low-resistance galvanometer is available, then a Rubens linear thermopile can be used. If the laboratory possesses a very sensitive galvanometer of high resistance, a bolometer might be used. A thermopile can be bought for £3. 6s. and a bolometer for about £6. If no galvanometer is available, it will be cheaper to buy a radio-micrometer (£17. 10s.) or, if the experimenter is experienced in glass-blowing and vacuum tube work, a radiometer might be made.

It must, of course, always be remembered that only the brightest spectra give readable deflections. A thermopile, for example, used with one of the most sensitive low-resistance moving-coil galvanometers on the market, will give readings if a Nernst filament is focused on the slit of the spectroscope, but not if a carbon glow-lamp filament is used instead.

In the thermopile only a very small fraction of the energy received by radiation is dissipated by the electric current as heat in the circuit. The rest is lost by conduction and convection, the radiation loss being very slight. Consequently, if

the air were pumped out and the convection loss annulled we would expect the temperature attained by the junction to be higher and the deflections on the scale to be greater. As a matter of fact, if the Rubens thermopile is put in a vacuum and the radiation is allowed to fall on it through a window, its sensitiveness is supposed to be increased seven times. The evidence on this point is, however, conflicting, probably owing to some experimenters not attaining a sufficiently high vacuum. The conductivity of a gas for heat remains constant until pressures of 1 mm. or thereabouts are reached. In any case, even if the sensitiveness is increased, there would be trouble in maintaining the necessary vacuum, and this would probably outweigh the additional sensitiveness obtained.

A disadvantage of the Rubens thermopile is the liability of the iron wire to rust through. On one occasion a thermopile that I had been using for a year and two reserve ones, that had been lying in a drawer, all rusted through simultaneously.*

There are no types of spectroscope on the market very suitable for mapping energy spectra. The common type with glass lenses and prism is unsuitable because glass transmits only from about $0{\cdot}330\mu$ to $2{\cdot}50\mu$. The limits, of course, vary considerably with the nature of the glass, but these may be taken as average values. Diffraction gratings are out of the question, because their spectra are fainter than prism spectra, and the chief difficulty in mapping energy spectra being to obtain readable deflections, it is necessary to economise light as much as possible. Also Paschen found that gratings distorted energy spectra, and in addition there is the difficulty due to the superposition of the different orders. The difficulty about using quartz spectrographs is that they require a considerable amount of adaptation. The limits of transmission of quartz may be taken as $0{\cdot}19\mu$ to $4{\cdot}0\mu$, about 10 per cent. of the incident light being transmitted through 1 cm. at these

* The Cambridge Scientific Instrument Co. has just brought out a new galvanometer and thermopile under the name of the Paschen galvanometer and thermopile. The galvanometer is of the Thomson astatic type and seems more sensitive than the Du Bois Rubens instrument. The thermopile is of the Rubens type, but has a mirror behind the elements.

wave-lengths. In order to go farther into the infra-red a rock-salt prism and lenses are necessary and they could not easily be substituted in the ordinary quartz spectrograph. If the laboratory possesses a quartz spectrograph, it will probably be better to use it; but if it does not, I strongly recommend two instruments which I have used myself and which I proceed to describe.

The first of these instruments employs the Wadsworth mirror-prism combination, which does not appear to be known in this country, although frequently used in research work in America. The Wadsworth mirror-prism combination consists of a prism and mirror mounted together on the prism table, with the plane of the mirror and the plane that bisects the refracting angle of the prism both meeting in the axis of rotation

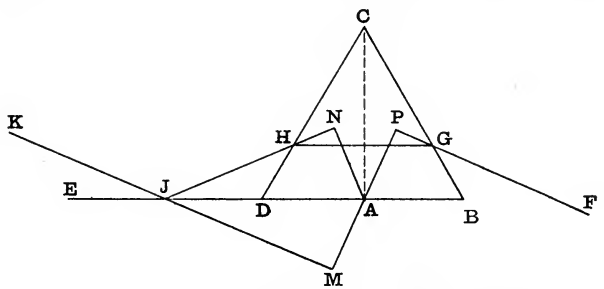


FIG. 16.

of the prism table. The diagram (Fig. 16) represents a special case of this arrangement; ED and CA, the traces of the planes in question, meet in A, through which the axis of rotation of the prism table passes.

Consider any ray FGHJK which passes through the prism at minimum deviation and is reflected by the mirror at J. Then JK is parallel to FG. The path of the ray through the prism GH is also parallel to the base of the prism BD. From A draw AP, AN and AM respectively perpendicular to FG, JH and KJ. Then AN=AM by equal triangles and AN=AP by symmetry; consequently AP=AM. Suppose that the ray FG is white light; the colour in this ray that suffers minimum deviation emerges along JK after passing through

the system. Now let the mirror-prism system be rotated through an angle about A, but let the ray FG remain fixed. Then AP and consequently AM remain fixed and the position of JK is unaltered by the rotation. But the colour of the light that emerges along JK is now different.

Suppose now that the single ray FG is replaced by a beam of parallel rays; each colour in turn, as it suffers minimum deviation, is undeviated and at the same time suffers the same constant parallel displacement.

The next diagram (Fig. 17) shows how these properties are taken advantage of. The mirror-prism combination is shown inside a rectangular box into which we are looking vertically down, the lid having been removed. The mirror is denoted by

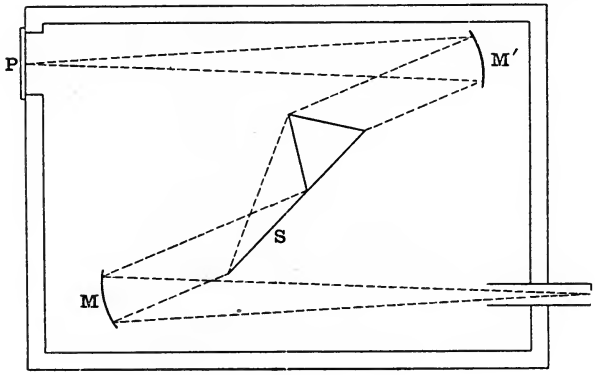


Fig. 17.

the letter S. The slit is attached to a piece of brass tubing which slides in a short piece of tube fixed in the side of the box. The light from the slit is rendered parallel by a concave mirror M, then passes through the mirror-prism combination, falls on the other concave mirror M′, and is brought to a focus on the photographic plate at P. Owing to the obliquity of the incidence, the distances of the slit and P from their respective mirrors are given not by $\frac{r}{2}$ but by $\frac{r \cos \phi}{2}$, where ϕ is the angle between the incident beam of light and the normal to the mirror.

If the ends of the spectrum are to come out sharp, the

photographic plate should be inclined at 79 deg. to the incident rays and not at right angles, as is shown by Fig. 17.

If the position of the mirrors be adjusted so that, when sodium light is used, the image of the slit in the minimum deviation position is in focus at P, and if the mirror-prism system be rotated, every wave-length comes into focus and at the same time suffers minimum deviation automatically when it reaches P. This is an immense advantage when a thermopile is being used. If a thermopile be fitted to a spectroscope with quartz prism and lenses, in addition to moving through the spectrum we should have to feel with the rack and pinion motion for the distance from the lens for which the bands were most distinct. Even in photographing the ultra-violet, automatic focusing is not to be despised. The spectrographs ordinarily used give the spectrum from about $600\mu\mu$ to $200\mu\mu$ on one photographic plate. The index of refraction of quartz varies from 1·54 to 1·65 within this range. Consequently, in order to get the whole plate in focus at once, it must be fixed with its surface making an angle of about 21 deg. with the axis of the camera lens, and it is a laborious process getting the angle and distance right.

The quartz prism always used, the Cornu double prism, gives a perfectly sharp image only with parallel light and when at minimum deviation. With a quartz collimating lens we can never have parallel light for the whole spectrum at once ; with a mirror we can. In a spectrograph of the usual type the rays falling on the centre of the plate satisfy the minimum deviation condition. With the arrangement described above any portion of the spectrum may be made to satisfy this condition at will. Finally a prism of different material or even different refracting angle can be substituted without any inconvenience. This is not the case with the ordinary quartz spectrograph.

The reason why concave mirrors have not been extensively used by instrument makers is because silver surfaces do not reflect the ultra-violet well, as will be seen from the following data due to E. Hagen and H. Rubens and taken from Landolt and Börnstein's tables :—

The table gives the percentage of incident light reflected at normal incidence by spiegel-magnalium, nickel and silver

λ.	Spiegel-magnalium 69Al+31Mg.	Nickel electrolytically deposited.	Silver chemically deposited.
0·251μ	67·0	37·8	34·1
0·288	70·6	42·7	21·2
0·305	72·2	44·2	9·1
0·316	...	...	4·2
0·326	75·5	45·2	14·6
0·338	...	46·5	55·5
0·357	81·2	48·8	74·5
0·385	83·9	49·6	81·4
0·420	83·3	56·6	86·6
0·450	83·4	59·4	90·5
0·500	83·3	60·8	91·3
0·550	82·7	62·6	92·7
0·600	83·0	64·9	92·6
0·650	82·7	66·6	93·5
0·700	83·3	68·8	94·6
0·800	84·3	69·6	96·3
1·0	84·1	72·0	96·6
1·5	85·1	78·6	98·4
2·0	86·7	83·5	...
3·0	87·4	88·7	...
4·0	88·7	91·1	...
5·0	89·0	94·4	...
7·0	90·0	94·3	...
9·0	90·6	95·6	...
11·0	90·7	95·9	...
14·0	92·2	97·2	...

mirrors for different wave-lengths. The silver mirror was one chemically deposited on glass and the light was reflected from the silver-air, not the silver-glass, surface. It will be noticed that at 316μμ only 4·2 per cent. is reflected, so that in the arrangement described above where the light is thrice reflected, if silver mirrors are used, only $6 \cdot 10^{-5}$ of the incident light would reach the photographic plate. The percentage reflected at those wave-lengths in the infra-red, for which no numbers are given, is always greater than 98·4 per cent., so that silver mirrors are very satisfactory for the visible spectrum and infra-red, although unsuitable for the ultra-violet. It should be noticed in passing that cheap concave lenses make quite good mirrors. They should be sent to an optical firm for silvering as the cost is trifling and it is difficult for an amateur to obtain a good

mirror on the silver-air surface, although quite easy to get a good one on the silver-glass surface.

It will be seen from the table that spiegel-magnalium reflects excellently throughout the whole spectrum. Unfortunately it does not keep well.* I have therefore used mirrors made of best quality solid nickel as a substitute for silver in the ultra-violet, and have mounted them in an instrument of somewhat different type, the second of those referred to on p. 99.

The arrangement of this instrument is shown by the diagram

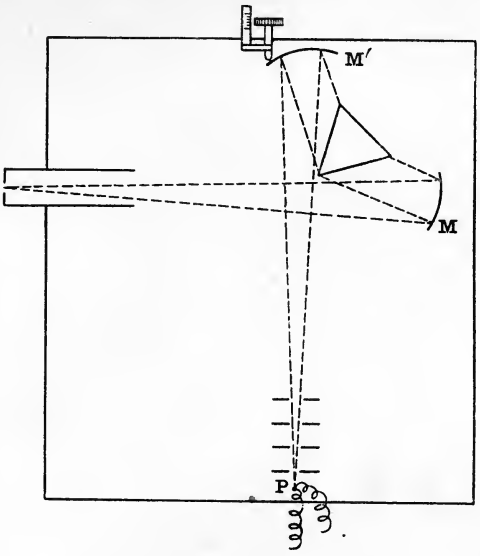


FIG. 18.

(Fig. 18). Light diverges from the slit, is rendered parallel by the fixed concave mirror M, passes through the fixed prism, which is set so that the middle of the spectrum suffers minimum deviation, falls on the mirror M′ and is brought to a focus on the thermopile at P. The mirrors, prism, slit and thermopile with its screens are all mounted on a mahogany base. The mirror at M′ can be rotated about a vertical axis through its centre by means of a micrometer screw ; hence, all the colours of the spectrum can be made in succession to pass across P. A

* Messrs. Kahlbaum now supply a spiegel-magnalium mirror which seems to keep.

cover comes down over the instrument when in use and makes it light-tight. The fraction of the incident light reflected by the two nickel mirrors in this arrangement at the most unfavourable place in the ultra-violet is $(0{\cdot}378)^2=0{\cdot}143$. In an ordinary spectrograph the fraction transmitted by the two quartz lenses in succession cannot be greater than 0·80. The ratio of the quantity of light received per unit area of photographic plate in the two cases, when we allow for the obliquity of the plate in the second case, is thus at least $\frac{0{\cdot}143}{0{\cdot}80 \sin 21^\circ}$ which is approximately equal to $\frac{1}{2}$. When we consider the convenience of focusing and the better collimation of the light, nickel mirrors are, I think, quite as good as quartz lenses even for work in the ultra-violet.

Both the above-described instruments can be employed as monochromatic illuminators. It will be noticed that they are also suitable for use with the radiomicrometer and radiometer,

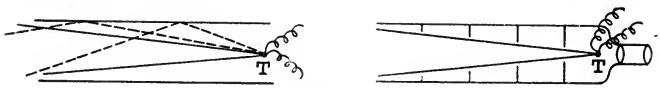


Fig. 19.

both of which cannot be moved during an experiment and hence cannot be employed with an instrument with a moving telescope arm.

Great care must be given to the mounting of the thermopile, or whatever the radiation measurer is, in order that the spectrum falling on it may be pure. The figure to the left below shows a faulty mounting. It represents a horizontal section of a tube containing the thermopile, a section of the latter being shown at T. The full lines represent the pencil of rays, which is to be measured, falling on T. The dotted lines show another pencil of rays which leaves the prism in a different direction, but which is reflected from the side of the tube so as also to reach T. The second pencil may be much more intense than the first, and since even a "dead black" surface such as the side of the tube reflects well at grazing incidence, it is clear that the second pencil may be a source of considerable error. The error arising in this way is said to be due to diffuse heat. The

diagram to the right in Fig. 19 shows how, by a proper arrangement of screens, this error may be prevented.

It is useful to have an eyepiece mounted behind the thermopile. A little light gets past between the latter and the screens, and by its means we are able to focus the thermopile on spectral lines and so calibrate the apparatus for the visible spectrum. Care must be taken that no heat enters through the eyepiece, when the thermopile is in use.

Few workers calibrate their apparatus for the infra-red by the methods given in the books. They mostly assume the indices of refraction for the materials of their prisms, for which there are tables now, and then calculate the wave-length from the deviation. If this method is unsuitable, a known emission or absorption spectrum may be used. For example, the absorption spectrum of water, which has been thoroughly investigated by E. Aschkinass (Wied. Ann. 55, p. 401, 1895), has well-marked absorption bands at 0·996, 1·500, 1·956, 3·02, 4·70 and 6·09μ. The band at 0·996μ shows up well when a layer of water 1 cm. thick is examined; the others require much thinner layers, $\frac{1}{20}$mm. and less.

The chief difficulty in mapping energy spectra being to obtain readable deflections, the length of the slit may bear a much larger ratio to the diameter of the collimating lens or mirror than is permissible in work in the visible spectrum. The spectral lines are then curved and their definition is not so good, but this does not matter owing to the breadth of the thermopile.

If an energy curve is not desired, an idea of the distribution of the energy in the spectrum may be obtained by the use of filters. In this case the thermopile is set up opposite the light source and the deflections noted when different filters are placed between. One advantage of this method is that it does not require the apparatus to be at all so sensitive. Filters that might be useful are plates of Uviol glass, red glass, and glass cells containing water, ferrous-ammonium sulphate in water or iodine in alcohol. Uviol transmits 50 per cent. of the incident light through a thickness of 1 mm. at 0·288μ. The red glass referred to is the common variety used for making signal lights. For finding the distribution of energy in the visible spectrum and ultra-violet the infra-red might be screened off with a 4-cm.

water filter, and then the deflection noted when Uviol glass, light crown, dense flint or red glass is placed in turn before the thermopile. Each of these in succession shifts the limit of transmission farther in the direction of increasing wave-lengths. For finding the distribution of energy in the infra-red, a set of water filters of decreasing thickness, a glass plate, and finally a quartz plate might be used. These would in succession shift the limit of transmission farther into the infra-red. In using filters, care should, of course, always be taken to allow for the reflection loss at the transparent region.

So much for energy spectra. Let us now consider briefly the subject of spectrophotometry. A great number of different spectrophotometers have been described and a discussion of the principal types is given in Kayser's "Spectroscopie," Vol. III., Chapter 1. There is no comprehensive article on the subject in English. Comparatively little work has been done in spectrophotometry, some of the instruments have really never been used, and I doubt even whether one or two have been made. There is no doubt whatever that accurate spectrophotometry is difficult. All factors bearing upon the measurements must be carefully studied. For this reason, if it is not intended to do much work in or spend much time on the subject, I think conditions should be kept as simple as possible, and I therefore suggest the following arrangement :—

A spectroscope should be mounted about the middle of a photometer bench with its collimator horizontal and at right angles to the bench and with its slit the same height as the two lamps whose spectra are to be compared. Close up to the slit should be mounted two total reflecting prisms and two pieces of ground glass A and B, as in Fig. 20. For the sake of clearness the pieces of ground glass are shown some distance from the prisms, but in reality they should be close up to them. The one lamp under comparison illuminates B which in turn illuminates *b*. The other lamp illuminates A and consequently *a*. An eye looking into the telescope sees consequently two spectra, one above the other, one spectrum being produced by each lamp, and the intensities may be compared for any particular wave-length by shifting the lamps along the bench until balance is obtained and then using the inverse square law. In applying

the inverse square law, distances should in each case be measured from the nearer piece of ground glass and not from the slit. To guard against want of symmetry, readings should be taken with the lamps interchanged.

The disadvantage of the above method is that the observer requires an assistant to move the lamps while he is observing the spectra; also that the dividing line between the spectra is not very sharp and hence the highest accuracy is not possible.

If greater accuracy is desired, an instrument must be obtained from one of the optical firms. The two spectrophotometers that seem to find a sale at present are the König-Martens spectrophotometer (F. Schmidt and Haensch, Berlin) and

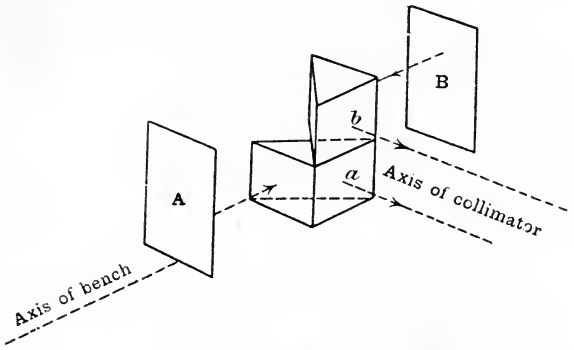


FIG. 20.

the Hüfner spectrophotometer (Hilger, London, Krüss, Optisches Institut, Hamburg). Schmidt and Haensch list two other types, but I do not think they are much used. Both the König-Martens and the Hüfner spectrophotometers are alike in having two slits on one collimator and in matching the intensities by the rotation of a nicol. There are, of course, other ways of matching the intensities, rotating sectors and micrometer slits. Rotating sectors require a motor to drive them, and during an operation such as spectrophotometry, in which so much depends on the psychological factor, some people find the noise of the motor disturbing. The chief difficulty in the way of regulating the brightness of a spectrum by altering the width of the slit is, that not only the intensity but also the purity of

the spectrum is being altered, and if the slit is opened very wide we obtain a distinct change of colour. Also, owing to diffraction effects, the intensity transmitted is not strictly proportional to the slit width. I think, therefore, that the rotation of a nicol is the best way of matching intensities.

In choosing an instrument, too much weight must not be laid on the accuracy with which the nicol can be set under the best conditions, for there are generally systematic errors greater than the error of the nicol setting. Freedom from systematic error, simplicity, convenience in handling and economy of light are the main essentials, and I think that on these points the Hüfner spectrophotometer is probably the best we have. The König-Martens instrument has been thoroughly worked out and gives very consistent readings, but is more complicated and extremely wasteful of light. It is also not so easy to get the

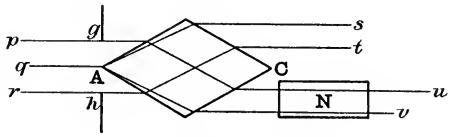


Fig. 21.

wave-length accurately when white light is used with it. I have had experience of both the König-Martens and the Hüfner, and have a decided preference for the Hüfner. I have also had experience of the Wild spectrophotometer, which depends on the disappearance of interference bands, and on all points it is much inferior to the other two.

The Hüfner spectrophotometer consists of a spectroscope, before the slit of which a Glan-Thompson prism N and a glass rhomb (the Hüfner rhomb) is brought (*see* Fig. 21). The edge A is ground very sharp and bisects the slit *gh*. If we disregard the polarising effect of the rhomb, the upper beam bounded by the rays *sAq* and *thr*, which illuminates the lower half of the slit, consists of natural light, and the beam bounded by the rays *ugp*, *vAq*, which illuminates the upper half of the slit, consists of light polarised in either a vertical or horizontal plane. Another nicol is inserted in the path of both beams. If we look into

eyepiece we see two spectra, one above the other, and by rotating this nicol we can alter their relative intensity.

The light which comes from the upper half of the slit must be plane-polarised before entering the second nicol, and the light which comes from the lower half of the slit must be unpolarised natural light. But it is partially polarised by both the Hüfner rhomb and the dispersion prism. The refracting angle of the latter is chosen so that these partial polarisations remove one another.

There is a wedge of neutral tinted glass, not shown in the figure, placed in the path of the upper beam immediately above the nicol in order to compensate the reflection and absorption loss in the latter. It would take too long to enter into all the details of a determination, but if, when the two fields are matched, the nicol makes an angle α with the position for extinction of

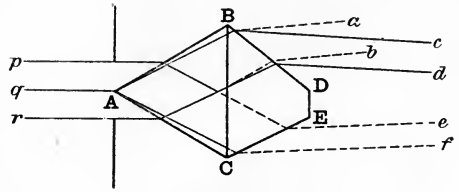


FIG. 22.

the one-half of the field, the ratio of the intensities for the wavelength in question is $\cos^2\alpha$.

I have recently made a change in the Hüfner spectrophotometer which, to my prejudiced judgment at least, is an improvement (Phil. Mag. (6), 15, p. 282, 1908). In place of the rhomb AC and the Glan-Thompson prism N, I use a single prism of the shape shown in the preceding diagram (Fig. 22):—

ABC is made of glass, for which $\mu_D = 1{\cdot}526$, the sides AB, BC, CA being each 2 cm. long. It is cemented to a prism of Iceland spar, BDEC, cut with its axis perpendicular to the plane of the paper. The angle D is 127° 12′, E is 115° 49′ and BCE is 64° 11′.

The action of the prism may be better understood by supposing the beams of light to go in the reverse direction—from the object glass of the collimator to the slit. The beam *qr* is

broken into two by the Iceland spar prism, *cd* being the ordinary beam and *ab* the extraordinary. The beam *pq* is broken into two, but only the extraordinary *ef* emerges, the ordinary being totally reflected at the surface CE. The beams *ef*, *cd* meet 15 cm. out in an elliptical spot of light measuring 2·0 cm. by 2·4 cm., the long axis being vertical. The beam *ab* is quite 2 cm. clear.

If, now, we have as source of light an incandescent mantle behind a screen, with an aperture at the proper place not much larger than 2·0 cm. by 2·4 cm., and if we look into the eyepiece we see two spectra, one above the other, polarised at right angles to one another. The ordinary component of the lower beam misses the slit entirely, while the extraordinary component of the upper beam misses the object glass of the collimator.

In order to measure the fraction of light transmitted through a piece of glass it is placed in succession in the path of the upper and lower beams and readings are taken. In comparing two sources, one is made to illuminate a piece of ground glass measuring 2·0 cm. by 2·4 cm., which is placed 15 cm. out in the position above referred to, while the lower beam from this piece of ground glass is stopped by a screen and replaced by a beam from a second piece just in front of CE, this second piece being illuminated from the side by the second source.

As in the original instrument, the relative intensity of the two spectra is altered by the rotation of a nicol. The chief advantage of my prism is that, as it plane-polarises both beams, it can be used with any dispersion prism whatever and not only with one of a particular refracting angle. In my instrument the ratio of the intensities is given by $\tan^2 a$.

We shall now leave spectrophotometry and give a short account of Ångström's pyrheliometer, which is perhaps the best instrument for measuring the intensity of a radiation in absolute measure. The references to Ångström's papers have been given on p. 95.

The pyrheliometer consists essentially of two metal strips, blackened on one side, and in every way similar. One is exposed to the radiation to be measured and the other, which is screened from the radiation by a double wall, is warmed by an electric current flowing through it. The strength of the current

is regulated so that the difference of temperature of the two strips, as read by a thermo-element, is zero. Then the energy radiated into the one strip is equal to the heat generated by the electric current in the other. Let q be the intensity of the radiation in gm. cals. per square centimetre per second, l, b the length and breadth of the strips, r its resistance per unit length, a the fraction of the incident radiation absorbed by the strip, and i the strength of the compensation current. Then

$$qalb = \frac{lri^2}{4 \cdot 2};$$

whence

$$q = \frac{ri^2}{4 \cdot 2\, ba}.$$

The constants a, b and r can be determined once for all. It is not necessary to make a correction for loss of heat by conduction, convection or radiation, as this loss is exactly the same for both strips. The instrument is designed so that the role of the strips is interchangeable.

The strips are made of platinum foil and are about 0·001 to 0·002 mm. thick, 2 mm. wide and 18 mm. long. The chief difficulty lies in the determination of the constant a, but Ångström estimates that it can be measured to at least 0·5 per cent.

It should be noted that since Ångström has measured the total radiation of the Hefner lamp and found it to be $2 \cdot 15\ 10^{-5}$ gm. cals. per square centimetre per second at 1 m. distance in a horizontal direction, anyone possessing a Hefner lamp can make absolute measurements of the intensity of a radiation with an ordinary thermopile or radiomicrometer. For it is only necessary to standardise the latter by exposing it to the radiation of the lamp.*

* In a recent article (Proc. Phys. Soc. 23, p. 1, 1910) Prof. H. L. Callendar criticises Ångström's pyrheliometer and describes some new methods for the absolute measurement of radiation.

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There are 15 Chapters, and the following is a synopsis of the Contents: Chapter I., Introductory—Chapter II., Electric Equipment—Chapter III., Structural Steelwork—Chapter IV., Power required to Drive Cranes—Chapter V., Mechanical Equipment—Chapter VI., Crane Arrangements—Chapter VII., Arrangement of Crane Mechanisms—Chapter VIII., Design of Crane Mechanisms—Chapter IX., Overhead Travelling Cranes and Gantry Cranes—Chapter X., Jib Cranes—Chapter XI., Building Slip Equipments—Chapter XII., Fitting-out Basin Cranes—Chapter XIII., Steelworks Cranes—Chapter XIV., Specifications—Chapter XV., Properties of Sections and Conductors.

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Cooper—*See* "THE ELECTRICIAN" PRIMERS, page 8.

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